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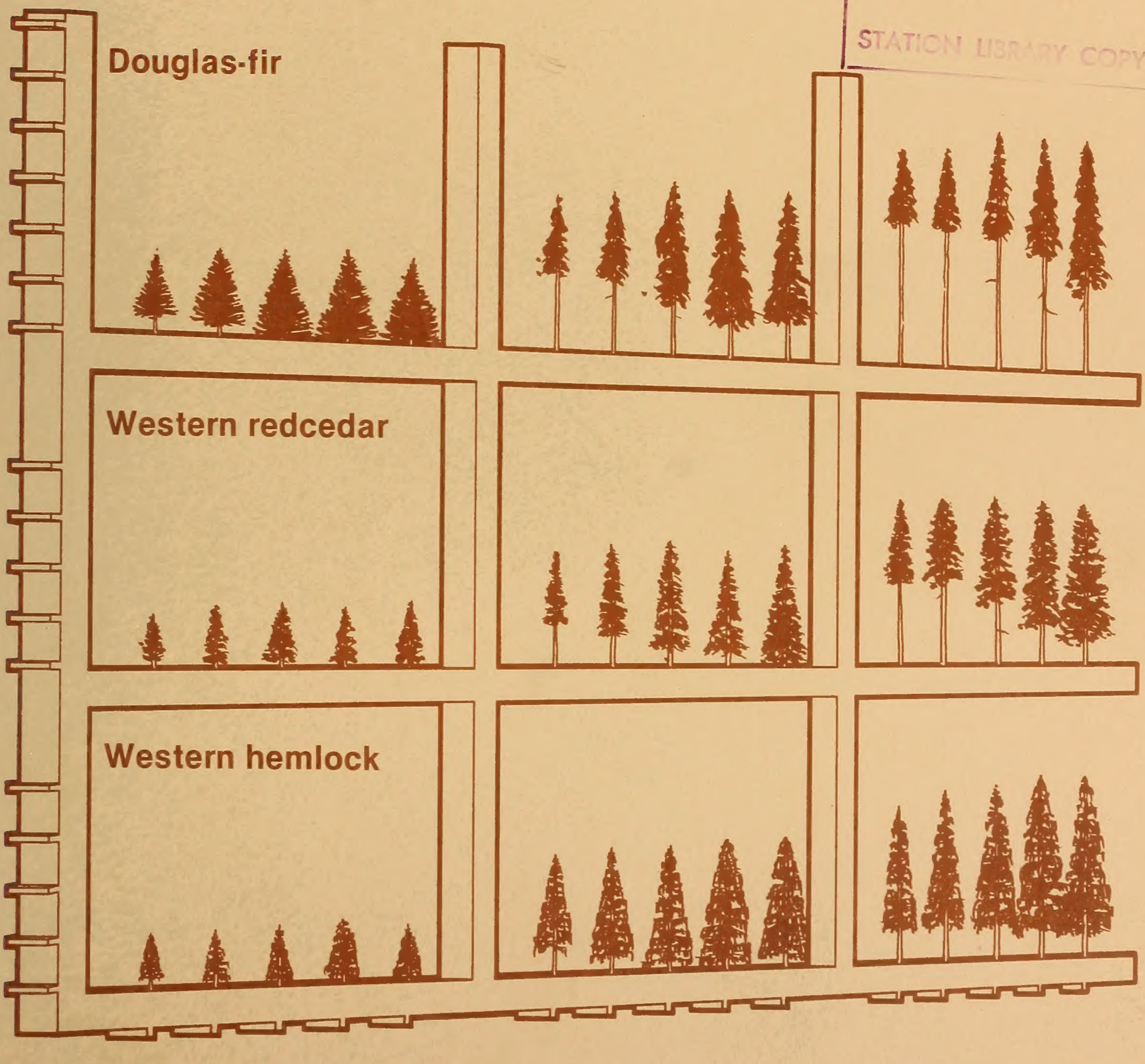
Development Over 25 Years of Douglas-Fir, Western Hemlock, and Western Redcedar Planted at Various Spacings on a Very Good Site in British Columbia

Donald L. Reukema and J. Harry G. Smith



Authors

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Abstract

Reukema, Donald L.; Smith, J. Harry G. Development over 25 years of Douglas-fir, western hemlock, and western redcedar planted at various spacings on a very good site in British Columbia. Res. Pap. PNW-RP-381. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; **1987.** 46 p.

Results of five spacing trials on the University of British Columbia Research Forest, covering a range of plantation spacings from 1 to 5 meters, showed that choice of initial spacing is among the most important factors influencing bole and crown development and stand growth and yield. The trials include Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*). The results to date should help managers to choose optimum spacings for their purposes. Initial wide spacings with rectangularities up to 2:1, such as 6 by 3 meters, resulted in efficient production of large trees of high value and satisfactory quality. Pruning of widely spaced trees to enhance quality of the lower bole is strongly recommended.

Keywords: Plantation spacing, (-growth, stand development, density, height increment, diameter increment, crown development.

Summary

Influences of plantation spacing on bole and crown development were studied in five trials established from 1957 to 1967 on a very productive site near Maple Ridge (Haney), British Columbia. Douglas-fir (*Pseudotsuga menziesii*) has grown much larger and produced more volume than western hemlock (*Tsuga heterophylla*) or western redcedar (*Thuja plicata*). The trials include spacings from 1 to 5 meters, rectangularities from 1:1 to 2:1, and some alternate rows of Douglas-fir and western hemlock. Results from 0.2-ha-plot, 49-tree-plot, rectangularity, Nelder-plot, and variable-block trials showed similar effects of spacing on growth of Douglas-fir.

Top heights were initially a little taller at close spacings because of more opportunities for natural selection of superior genotypes and microsites, but top heights are now similar at all spacings; initial advantages of natural selection for the many trees planted at close spacings have disappeared. Average heights are now shorter at close spacing. Decreases in heights to dead and live crowns and increases in diameter of lower boles, taper, and crown size occurred as spacing increased. Basal area and volumes per hectare increased as spacing decreased until onset of density-related mortality from snow damage and similar causes.

Although it is difficult to establish plantations on such productive sites because of heavy competition from brush, potential gains from initial wide spacing and pruning are impressive. The results to date should help managers to choose optimum spacings for their purposes. We concluded that initial wide spacings with rectangularities up to 2:1, such as 6 by 3 m, result in efficient production of large trees of high value and satisfactory quality. Pruning of widely spaced trees to enhance lower bole quality is strongly recommended.

Contents

Introduction

Influences of initial spacing on stand development are of considerable economic and biological importance. Much has been learned from a study of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) at the Wind River spacing trials on site IV land in southwest Washington (Reukema 1979), but foresters in the Pacific Northwest lack published data on establishment and early growth of Douglas-fir and associated species on good sites. This paper reports development of Douglas-fir, western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western redcedar (*Thuja plicata* Donn ex D. Don) on site I land at the University of British Columbia (UBC) Research Forest near Maple Ridge (Haney), British Columbia.

The results summarized in various progress reports (Smith 1983, Walters and Smith 1973) have been synthesized and further evaluated for this paper. Our information should be useful to managers interested in growing trees to meet a wide range of managerial objectives.

The Study

The Study Area

The UBC Research Forest is north of Maple Ridge, in the Fraser River Valley; latitude 49°18′ N., longitude 122°35′ W. The five trials are all within an area of less than 45 ha, and the most distantly separated plots are less than 1 km apart (fig. 1). The area is about 180 m above sea level on land that slopes gently to the southwest. The soil is a gleyed, micro-podzol with mull humus and with sandy loam to loamy sand texture. Precipitation includes an average of 2040 mm of rain and 1260 mm of snow per year, which yields an annual water equivalent of 2166 mm; summer droughts are common. Daily temperature averages about 9 °C.

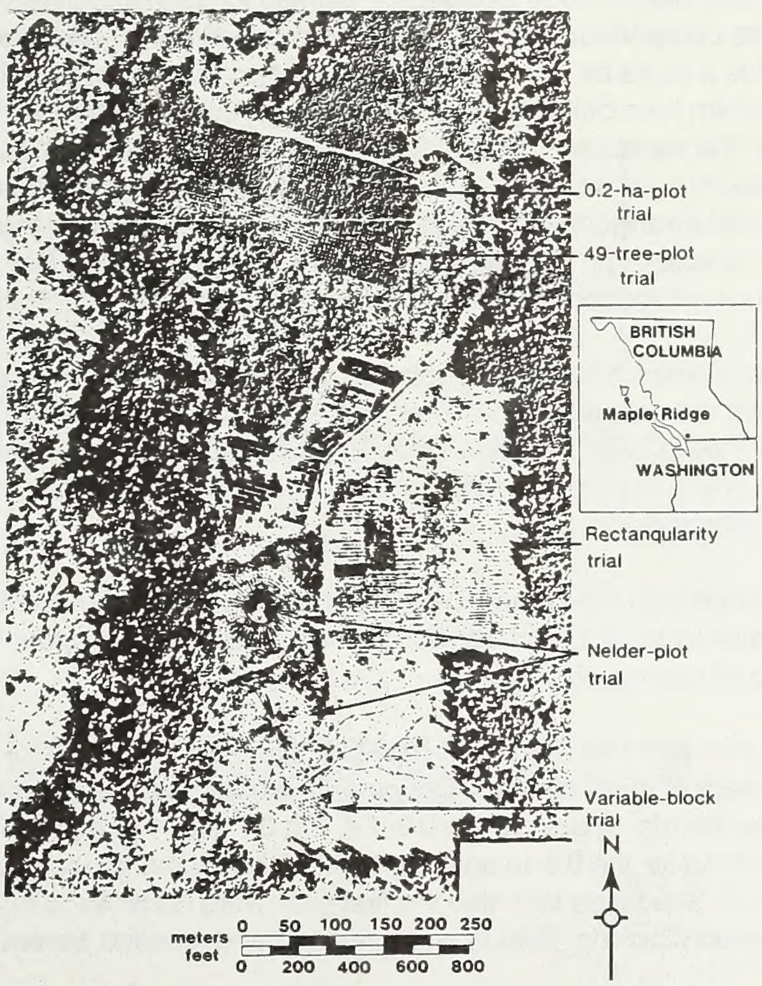

Figure 1—Relative locations of the spacing trials at the University of British Columbia Research Forest near Maple Ridge (Haney), British Columbia.

The area on which the first trials were established supported old-growth Douglas-fir, western hemlock, and western redcedar until 1955 when it was logged. The stand in that area included a few 500- to 800-year-old Douglas-fir. The apparent site indices indicated by the old-growth trees were about 61 m at 100 years for Douglas-fir and 40 m at 100 years for cedar and hemlock; the corresponding site index for Douglas-fir at breast-height age 50 is approximately 43 m. The nearby area where a second set of trials was established was logged in 1963; age of Douglas-fir in that area averaged 106 years.

The spacing trials were established soon after the areas were logged. Site preparation was done by bulldozer; large stumps were not removed from the areas logged in 1955. Logging slash was piled and burned. Some soil compaction occurred during site preparation. The site supported substantial lesser vegetation and hardwoods.

The Trials

The trials were established not only to assess effects of spacing on tree and stand development but also to determine the practicality and efficiency of different experimental designs (Smith 1959, 1978). For this report, the trials are designated (1) 49-tree-plot trial, (2) 0.2-ha-plot trial, (3) rectangularity trial, (4) Nelder-plot trial, and (5) variable-block trial. All trials are being continued.

Most trials were planted with 2+0 stock of suitable provenance that was grown nearby at the Green Timbers Nursery. The Nelder-plot and variable-block trials were planted with extra large (2+2) stock — either nursery stock or, in some cases, local wildlings that were grown in transplant beds for an additional 2 years before being outplanted.

All five trials include Douglas-fir planted in pure stands at various spacings; this facilitates comparison among the different experimental designs. The 49-tree-plot trial provides a basis for comparing relative response of Douglas-fir, western redcedar, and western hemlock to a range of spacings; this is supplemented by data from Nelder-plot 2 and the variable-block trial. The rectangularity trial provides data needed to assess responses of mixed (50:50) Douglas-fir/western hemlock stands to various spacings and spatial arrangements; it also enables a comparison with pure Douglas-fir planted at the same spacings. Sitka spruce (*Picea sitchensis* (Bong.) Carr.) was included only as a minor component of Nelder-plot 2 and the variable-block trial.

Establishment of spacings and all measurements taken through 1975 were in imperial units; the data were converted to metric units for this report. Measurements taken since 1975 have been in metric units. Reported spacings have been rounded to the nearest decimeter for ease in reading; corresponding per-hectare values were derived from the exact spacings.

A summary of these trial designs and the periods of evaluation included in this report is shown in table 1, and additional detail is given in the appendix (table 11). A brief description of each design follows.

49-tree-plot trial — The 49-tree-plot trial tests the effects of square spacings on development of three species (Douglas-fir, western redcedar, and western hemlock) grown in pure stands. Spacings are 0.9, 1.8, 2.7, 3.7, and 4.6 m (3 to 15 feet). Small plots range from 0.008 ha for the 0.9-m spacing to 0.102 ha for the 4.6-m spacing; each has two replicates (fig. 2). Seedlings that died the first year were replaced with 3+0 stock to maintain the desired stocking. Stands were cleaned and weeded several times.

Table 1—Summary of trial designs and their periods of evaluation for this report

Trial	Species 1/	Number of Spacings	Nominal growing space	Stock used	Establishment date	Most recent data: Date	Most recent data: Age 2/
			m^2/tree				
49-tree plots	DF	5	0.8-20.9	2+0	Fall 1957	Fall 1980	25
	WRC	5	.8-20.9	2+0	Fall 1958	Fall 1981	25
	WH	5	.8-20.9	1+1	Spring 1959	Fall 1981	25
0.2-ha plots	DF	5	.8-20.9	2+0	Fall 1957	Fall 1980	25
	WH	1	.8	1+1	Spring 1959	Fall 1981	25
Rectangularity	DF	9	.8-15.1	2+0	Spring 1967	Fall 1984	20
	DF+WH	9	.8-15.1	2+0	Spring 1967	Fall 1984	20
Nelder-plot 1	DF	3/ 15	.8-24.4	2+2	Fall 1965	Fall 1981	20
Nelder-plot 2	DF	3/ 15	.8-24.4	2+2	Spring 1966	Fall 1981	20
	WH	3/ 15	.8-24.4	4/ ?+2	Spring 1966	Fall 1981	20
	WRC	3/ 15	.8-24.4	4/ ?+2	Spring 1966	Fall 1981	20
	SS	3/ 15	.8-24.4	2+2	Spring 1966	Fall 1981	20
Variable-block	DF	3	.8-20.9	2+2	Spring 1966	Spring 1984	22
	WH	2	7.5-20.9	2+2	Spring 1966	Spring 1984	22
	WRC	2	.8- 3.3	4/ ?+2	Spring 1966	Spring 1984	22
	SS	1	3.3	2+2	Spring 1966	Spring 1984	22

1/ DF = Douglas-fir, WRC = western redcedar, WH = western hemlock, SS = sitka spruce.
2/ Total age of trees from seed.
3/ Continuous increase in spacing on successive arcs.
4/ ? = wildings of unknown age.

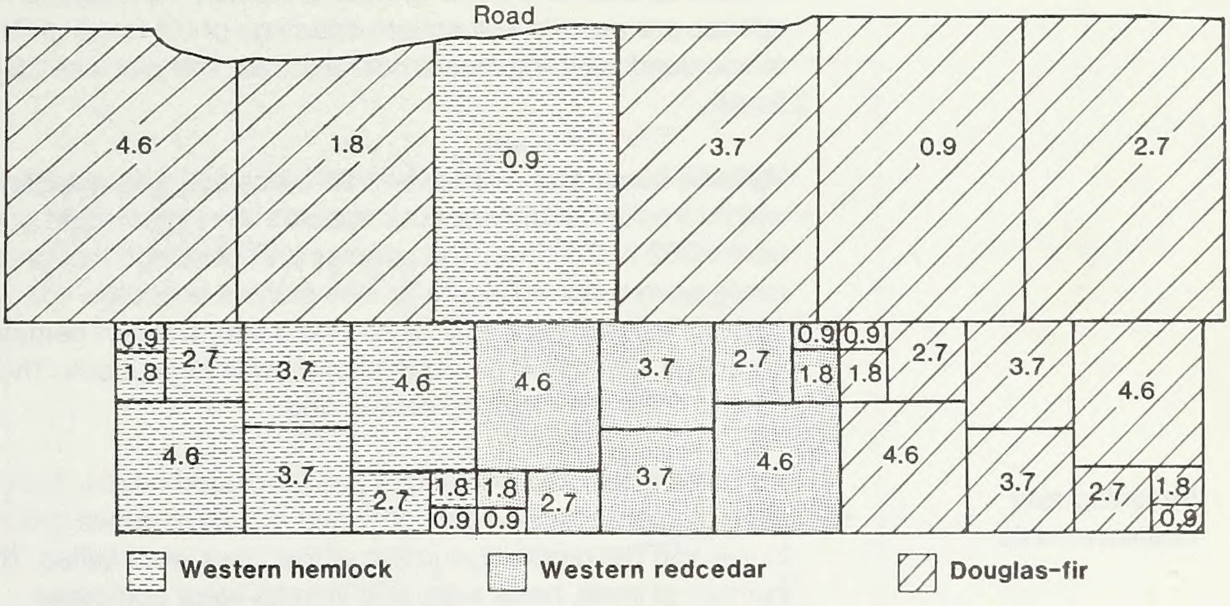

Figure 2—Layout of the 0.2-ha-plot and 49-tree-plot trials. Numbers indicate spacing between trees in meters. DF = Douglas-fir, WH = western hemlock, and WRC = western redcedar.

0.2-ha-plot trial — The 0.2-ha-plot trial tests the effects of square spacings of 0.9, 1.8, 2.7, 3.7, and 4.6 m (3 to 15 feet) on development of Douglas-fir; it also includes western hemlock at the 0.9-m spacing. Large plots vary from 0.198 to 0.251 ha, plus buffers; they are not replicated (fig. 2). Seedlings that died the first year were replaced with 3+0 stock to maintain the desired stocking. Stands were cleaned and weeded several times.

Rectangularity trial — The rectangularity trial tests the effects of nine spacing arrangements, with rectangularity ranging from 1:1 to 2:1: 0.9 by 0.9, 1.4 by 1.4, 1.8 by 1.8, 2.7 by 1.8, 3.7 by 1.8, 2.7 by 2.7, 3.7 by 2.7, 4.6 by 2.7, and 5.5 by 2.7 m (3 by 3 to 18 by 9 feet). Each spacing arrangement is used for pure Douglas-fir and for alternating rows of Douglas-fir and western hemlock. Plot size generally increases with increased spacing and ranges from 0.033 ha for one plot at close spacing to 0.590 ha for plots at the widest spacing (fig. 3). Dead seedlings were not replaced. Plots were cleaned and weeded several times.

Nelder-plot trial — Nelder-plot 1 tests a continuous range of spacing of Douglas-fir along 36 spokes and constant spacing along 12 spokes that radiate from the center of the circular plot. (See Nelder (1962) for a complete discussion of the designs.) Thirty-six spokes are used for a test of spacings ranging from about 0.9 by 0.9 to 4.9 by 4.9 m (3 by 3 to 16 by 16 feet). Twelve spokes are used to test effects of rectangularity ranging from about 1:1 to 4:1, all trees having 9.3 m^2 of available growing space; that is, spacings range from about 3.0 by 3.0 to 6.1 by 1.5 m (10 by 10 to 20 by 5 feet) (fig 4). The plot was planted with large stock; dead seedlings were not replaced. The plot was cleaned and weeded several times.

Nelder-plot 2 tests a continuous range of spacings of four species along 48 spokes. The sequence of three spokes of Douglas-fir, three spokes of western hemlock, three spokes of Sitka spruce, and three spokes of western redcedar is replicated four times. All 48 spokes are used to test square spacings of 0.9 to 4.9 m. The plot was planted with large stock; dead seedlings were not replaced. The plot was cleaned and weeded several times.

Variable-block trial — The variable-block trial was established on an area with moist to wet microsite conditions. Four species were planted, in pure stands, on plots ranging from 0.032 to 0.301 ha. The species and spacings thought to be most suited to each microsite were used. Douglas-fir was planted at square spacings of 0.9, 1.8, and 4.6 m (3 to 15 feet); western redcedar at 2.7 and 4.6 m; western hemlock at 0.9 and 1.8 m; and Sitka spruce at 1.8 m. The plot was planted with large stock. There was no replanting and, prior to 1984, no cleaning or weeding.

Sampling and Measurements

Variables measured on sample trees included height, d.b.h. (diameter at breast height), stem diameters at the root collar and at 2.74 m above ground, crown width, and heights to live and dead crown; number of live trees were tallied. The per-hectare values for number of trees, basal area, and volume were computed.

Heights of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials were measured annually through age 9, and heights of hemlock in the 49-tree-plot trial were measured annually for the first 8 years. Subsequent heights in these trials and heights in other trials were measured at intervals of 1 to 7 years.

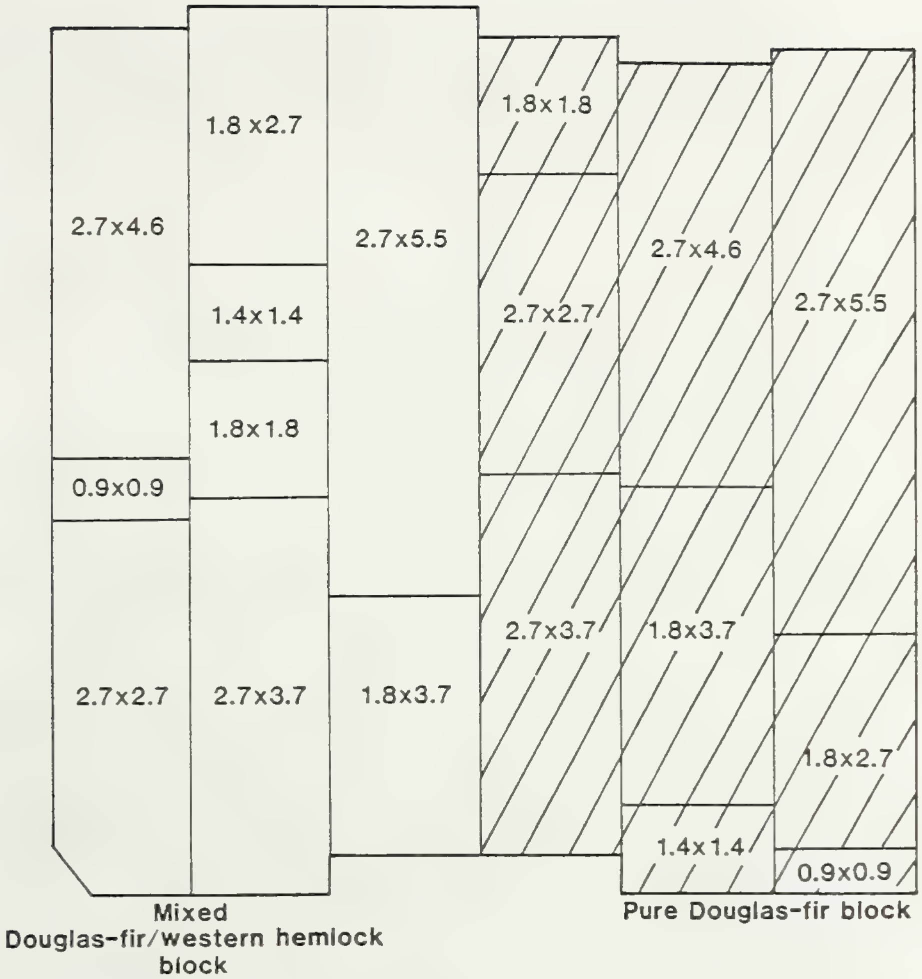

Figure 3—Layout of the rectangularity trial.

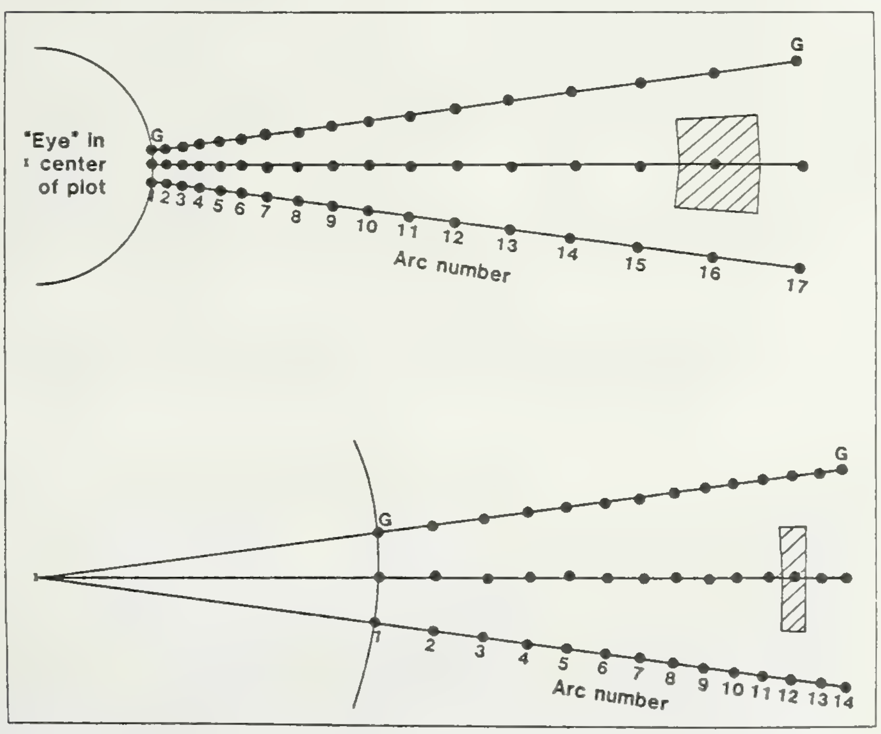

Figure 4—Spatial arrangement of trees in the Nelder-plot trial. Above: square spacings used on plots 1 and 2. Below: rectangular spacings used on one quadrant of plot 1. (Crosshatched areas show the nominal growing space available to a tree.)

In the 49-tree-plot trial, heights were measured on alternate rows of trees; the sample size ranged from 21 to 28 trees per plot, less adjustments for missing trees. On the 0.2-ha-plot and rectangularity trials, heights were measured on subsamples of various sizes; at the last measurement (age 20) on the rectangularity trial, all trees were measured for height. In the Nelder-plot-trial, all trees were measured for height each time.

Measurements of d.b.h. were begun in the 49-tree-plot trial at age 8 for Douglas-fir and at age 10 for cedar and hemlock. Trees were measured at irregular intervals thereafter, and all trees were measured each time. Measurements of d.b.h. were begun at age 13 in the 0.2-ha-plot trial, at age 10 in the rectangularity trial, and at age 11 in the Nelder-plot trial; diameter measurements were taken for all trees.

Measurements of crown width, height to live and dead crown, and diameters at root collar and at 2.74 m were made on the same trees as were measured for height in the 49-tree-plot trial, except for Douglas-fir at age 25. In other trials, and on the 49-tree Douglas-fir plots at age 25, these variables were measured only on the center trees of fully stocked subplots.

Fully stocked subplots — Initial planting gaps and subsequent mortality reduced planned density by various degrees and reduced precision of estimates of initial spacing effects. Fully stocked subplots were established to quantify effects of spacing "without error." Each fully stocked subplot consists of a square block of nine trees—a center tree surrounded by eight competitors—that represented initial full stocking. All nine trees were alive at the time the subplot was established, but some have died since. Some of the nine trees may be common to more than one subplot.

Measurements made on center trees included diameters at root collar, breast height, and 2.74 m above ground; height to base of dead and live crown; total height; and crown width. Each time the center trees were measured, the eight surrounding trees were also measured for d.b.h.

Subsequent Treatments

Subplots in the 49-tree-plot and 0.2-ha-plot trials were identified and measured in July 1974. For the 49-tree-plot trial, six subplots were established for each spacing of each species (three subplots per plot) for a total of 90 center trees. For the 0.2-ha-plot trial, six subplots were established in each of the six plots (five Douglas-fir and one hemlock) for a total of 36 center trees. These 126 center trees and their surrounding trees were remeasured after the 1976, 1980 or 1981, and 1983 growing seasons.

Fully stocked subplots were established more recently in the rectangularity and variable-block trials. The number of subplots in these trials vary irregularly, with survival, from one plot to another.

In addition to replanting, weeding, and cleaning, other "treatments" were superimposed on some plots.

Pruning — On most plots, branches were removed (brashed) to a height of about 2 m for easy access and to make the plots more suitable for demonstration purposes. In the 49-tree-plot and 0.2-ha-plot trials all surviving trees in the centers of the 126 fully stocked subplots were pruned in 1977 to a height of about 6 m; this was done to determine effects of pruning and spacing on the quality of tree bole.

Thinning — In the plots at the 0.9- by 0.9-m and 1.4- by 1.4-m spacings in the mixed Douglas-fir/hemlock block of the rectangularity trial, portions of each plot were thinned diagonally (to preserve the species mixture) in 1974: On one third of the plot, every third row of trees was cut and on another third of the plot, every second row of trees was cut. In Nelder-plot 1 (pure Douglas-fir), all trees in spokes 1-24 of arc 2 and in spokes 13-24 of arc 4 were cut in 1974: Thus, in quadrant 1, trees in arc 3 were released on one side; in quadrant 2, trees in arc 3 were released on two sides and trees in arc 5 were released on one side.

Results and Discussion

The greatest amount of information available is from the 49-tree-plot and 0.2-ha-plot trials, so our attention focuses on those trials. Trees in those two trials are the same age, and the trials are immediately adjacent. Data were available for trees up to age 25, the early mortality had been replaced, and there was information on crown development and yields per hectare. The other trials are younger, but provided supplementary information.

All five trials provided information on development of Douglas-fir. Only the 49-tree-plot trial provided substantial data on relative development of three species—Douglas-fir, western redcedar, and western hemlock. The rectangularity trial provided some information on comparative development of pure Douglas-fir and western hemlock grown in mixture. The hemlock, cedar, and spruce components of the Nelder-plot and variable-block trials are minor and provided little information.

The 49-Tree-Plot and 0.2-ha-Plot Trials

We discuss results from the 49-tree-plot and 0.2-ha-plot trials in terms of (1) bole dimensions and form—height, diameter, stem form; (2) crown size and shape—crown width, height to live crown, crown length and crown ratio, crown shape; and (3) stand development per hectare—survival and mortality, d.b.h. frequency distribution, basal area, total-stem volume, merchantable volume.

Average bole and crown dimensions for trees in the 49-tree-plot trial at age 25 are shown in table 2. For d.b.h. and height, these are the averages of all live sample trees (trees that were measured for height). The other variables reported were measured on these same sample trees for cedar and hemlock; for Douglas-fir, the other variables were estimated from regressions fitted to data from fully stocked subplots.

Relative bole and crown sizes of the three species at ages 12, 20, and 25 are shown in figure 5, which is a synthesis of observed averages for the 49-tree-plot trial. Douglas-fir has obviously grown bigger and taller than cedar and hemlock. At initial spacings of 0.9 and 1.8 m, crowns began to lift early, remained narrow and short, and supported small trees with little taper. At initial spacings of 3.7 and 4.6 m, crowns spread wide, lifted late, and supported much larger and more tapered boles.

Trends of tree and stand development over time prior to age 25 are presented graphically in figures 6-17. All trends are shown as functions of age. Some trends are also plotted as functions of attained mean height. The advantage of expressing effects of spacing on other variables as functions of height (for the time trend) is that it facilitates comparing stands planted at common spacings that grow at different rates. This facilitates comparisons among species grown in the UBC trials. It also facilitates comparisons within species for stands growing at different locations, such as Douglas-fir grown in the UBC trials vs. the Wind River trials.

Table 2—Average bole diameters, stem form, and crown dimensions of sample trees at age 25 in the 49-tree-plot trial, by species and by spacing[1]

		Diameters			Stem form		Crown dimensions					
Spacing	Height	RCD	DBH	D2.7	H/D	D2.7/DBH	CW	HLC	HDC	CL	CL/H	CL/CW
- - - Meters - - -		- - Centimeters - -					- - - - Meters - - - -					
					DOUGLAS-FIR							
0.9	20.1	17.0	14.6	14.0	138	0.96	2.7	12.2	--	7.9	0.39	2.9
	18.2	15.2	13.1	12.5	139	.95	2.5	11.6	--	6.6	.36	2.6
1.8	18.6	20.6	16.9	15.6	110	.92	2.5	11.1	--	7.5	.40	3.0
	20.9	19.3	16.2	15.0	129	.93	2.6	12.1	--	8.8	.42	3.4
2.7	20.5	26.5	21.5	19.8	95	.92	3.0	10.6	--	9.9	.48	3.3
	21.8	29.6	23.9	22.0	91	.92	3.2	10.8	--	11.0	.50	3.4
3.7	20.7	34.6	27.7	25.6	75	.92	3.8	8.9	--	11.8	.57	3.1
	22.1	31.9	25.9	23.9	85	.92	3.8	9.7	--	12.4	.56	3.3
4.6	21.3	35.9	29.3	27.2	73	.93	4.7	7.6	--	13.7	.64	2.9
	19.6	36.9	29.9	27.8	66	.93	4.6	6.8	--	12.8	.65	2.8
Average	20.4					.93						3.1
					WESTERN REDCEDAR							
0.9	12.3	16.7	10.4	9.8	119	.94	2.1	6.6	2.2	5.7	.46	2.7
	12.8	18.6	11.5	10.7	111	.93	2.6	5.0	2.1	7.8	.61	3.0
1.8	14.3	25.3	15.7	14.3	91	.91	2.8	6.4	2.3	7.9	.55	2.8
	14.3	25.8	17.2	15.2	83	.88	3.1	5.0	2.1	9.3	.65	3.0
2.7	13.6	34.5	21.0	17.5	65	.83	3.6	3.9	1.5	9.7	.71	2.7
	16.1	38.0	24.6	23.2	65	.94	4.2	3.9	1.8	12.2	.76	2.9
3.7	12.8	28.6	20.5	17.2	62	.84	4.0	2.1	.7	10.6	.83	2.6
	15.5	37.0	26.0	21.4	59	.82	4.6	2.4	0	13.1	.85	2.8
4.6	14.4	38.0	26.0	20.0	56	.77	5.5	2.1	0	12.3	.85	2.2
	15.2	31.3	27.0	22.0	56	.81	4.5	2.0	1.2	13.2	.87	2.9
Average	14.1					.86						2.8
					WESTERN HEMLOCK							
0.9	11.8	12.8	10.1	9.6	117	.95	2.4	2.5	2.1	9.3	.79	3.9
	11.5	10.8	9.2	8.5	125	.92	2.5	2.8	1.7	8.7	.76	3.5
1.8	12.3	14.9	11.8	10.9	104	.92	3.5	3.3	1.2	9.0	.73	2.6
	12.5	17.1	13.6	12.9	92	.95	3.5	2.8	1.6	9.7	.78	2.8
2.7	12.1	18.7	13.8	13.0	86	.94	4.6	2.7	1.6	9.4	.78	2.2
	12.0	20.2	15.0	14.4	80	.96	3.7	2.6	1.9	9.4	.78	2.5
3.7	13.2	19.5	17.1	16.0	77	.94	4.9	2.1	1.7	11.1	.84	2.3
	14.0	26.5	19.2	18.4	73	.96	4.5	2.3	1.6	11.7	.84	2.6
4.6	12.6	20.8	16.6	16.0	76	.96	4.4	1.8	0	10.8	.86	2.4
	12.8	23.1	17.4	16.5	73	.95	4.3	2.1	1.1	10.7	.84	2.5
Average	12.5					.94					.80	2.7

-- = not applicable.
1/ Abbreviations: RCD = root collar diameter; D2.7 = diameter at a height of 2.7 m; H/D = ratio of height to d.b.h.; CW = crown width; HLC = height to live crown; HDC = height to dead crown; and CL = crown length.

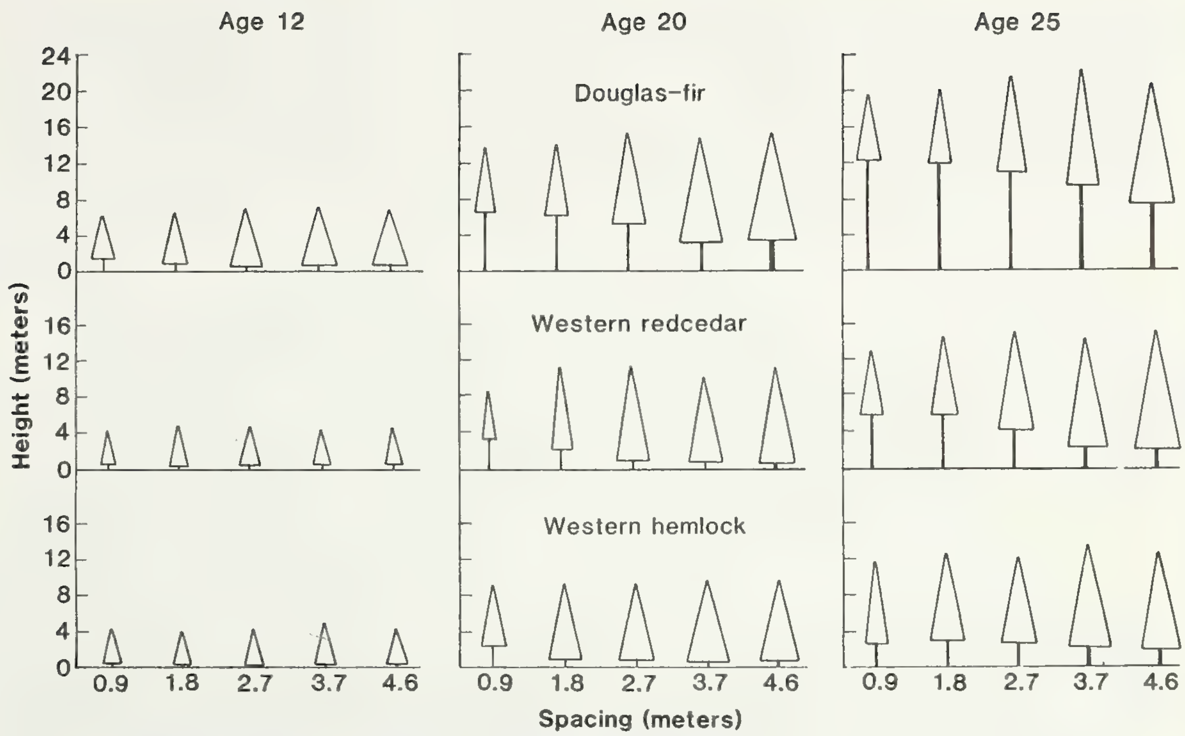

Figure 5—Relative bole and crown sizes of Douglas-fir, western redcedar, and western hemlock at ages 12, 20, and 25 in the 49-tree-plot trial.

For most variables, trends over time were consistent among species and among spacings for spacings of 1.8 to 4.6 m. Trends for the 0.9-m spacing were commonly quite irregular, mostly because of the greater mortality at this close spacing. There were differences in rates of development and, thus, in attained levels.

Generally the 0.2-ha-plot trial exhibited the same trends as the 49-tree-plot trial. The one major exception was mortality of Douglas-fir at the 0.9-m spacing, which was much greater in the larger plot (0.2-ha-plot trial), mostly because of snow press.[1]

Height — For all three species, spacing had little effect on height. The small differences among spacings in curves of both top height and mean height as functions of age are not consistently related to spacing; they include irregularities (fig. 6).

Top height — Top heights were initially a little taller at close spacings because of more opportunities for natural selection of superior genotypes and microsites; this is consistent with a phenomenon hypothesized by Mitchell and Cameron (1985). These initial natural selection advantages for the many trees planted at close spacings disappeared, however, as height growth of dominant trees was repressed by intense competition for growing space. Trends of Douglas-fir top heights over time closely followed Bruce's (1981) curve for site index 45 m at breast-height age 50. Apparent trends in top height were irregular, and there was no clear effect of spacing on current top height for any of the three species. Data suggest that top heights at age 25 might have been greatest at intermediate spacings; and recent growth tended to be least at the closest spacing. Whether or not future height growth will be substantially favored by initial wide spacings, as at Wind River (Reukema 1979), remains to be seen.

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[1]Snow press means that snow pressed tree crowns out of the canopy and contributed to the eventual fall to the ground of the tree, individually and in clumps.

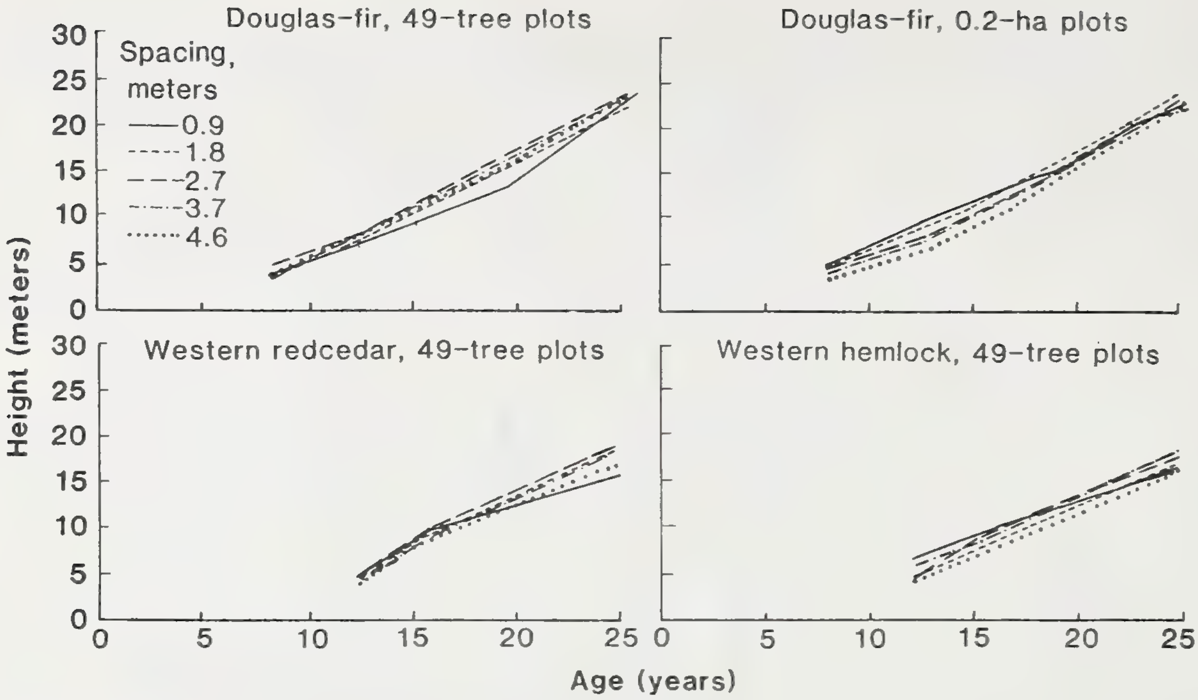

Figure 6a—Top height (100 largest trees per hectare), by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

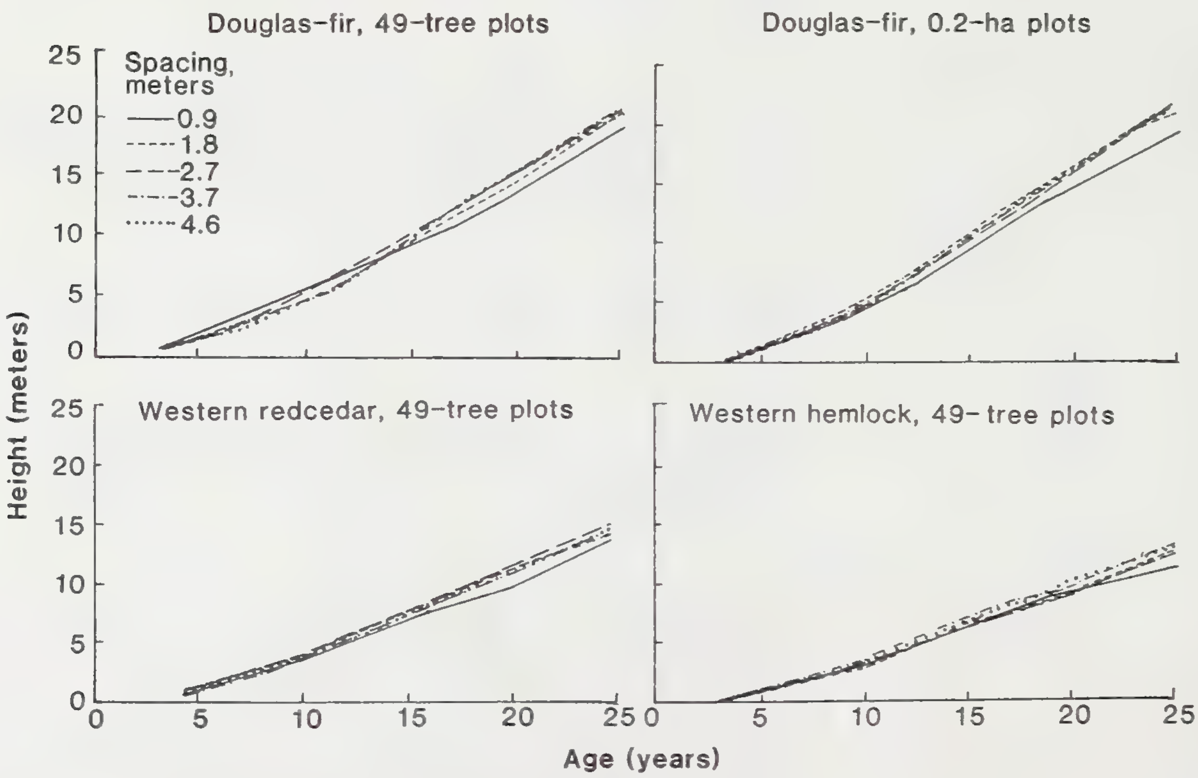

Figure 6b—Mean height, by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

Mean height — Relative to top heights, mean heights generally increased with increased spacing. At age 25, the difference between top height and mean height of Douglas-fir on the 0.2-ha-plot trial ranged from about 3.8 m at the 0.9-m spacing to 0.8 m at the 3.7-m spacing. The mean height curves in recent years were consistently lowest for the 0.9-m spacing. The curves for the 0.9-m spacing usually reached this lowest position by abrupt shifts in position, which might be associated with breakage or might reflect sampling and measurement errors.

For Douglas-fir in the 49-tree-plot trial, mean heights at age 25 averaged 20.4 m; the average for the 0.9-m spacing was about 6 percent shorter. There is no clear indication that differences are becoming greater. Trends of apparent height growth in the 0.2-ha-plot trial were more irregular, but differences generally showed no consistent relation to spacing; average height at the 0.9-m spacing was a little shorter than heights at the wider spacings. Heights at age 26 averaged 20.2 m; the average for the 0.9-m spacing was about 7 percent shorter.

For western redcedar, the greatest separation of curves apparently occurred between ages 16 and 20. Heights at age 25 averaged 14.1 m; the average for the 0.9-m spacing was about 11 percent shorter. For western hemlock, trees were tallest at the 3.7-m spacing. At age 25, average height for all spacings was 12.5 m; the average for the 0.9-m spacing was 6 percent shorter and that for the 3.7-m spacing was 9 percent taller.

Diameter — Average d.b.h. of all three species was strongly influenced by spacing (fig. 7). Curves of diameter as a function of age are generally quite consistent, despite some minor irregularities. The curve for the 0.9-m spacing is always the lowest (smallest diameters), and elevation of curves generally increases with increased spacing. There was some crossing of curves in the past because of differences in early growth rates that were associated with factors other than spacing.

Apparent differences between the 49-tree-plot and the 0.2-ha-plot trials in recent trends over time (diameter has leveled off in the 0.2-ha-plot trial but not in the 49-tree-plot trial) are partly associated with differences in the amount of time between measurements; this is not the complete explanation, however. Other irregularities in elevation of curves for specific species are probably also associated with site differences.

For Douglas-fir in the 49-tree-plot trial, differences among all spacings widened over time. By age 25, quadratic mean d.b.h. (Dg) was 2.14 times as large at the 4.6-m spacing as at the 0.9-m spacing. Average diameters in the 0.2-ha-plot trial at age 13 (the first measurement) were virtually the same at all except the 0.9-m spacing. Thereafter, differences among the 1.8- through 4.6-m spacings steadily widened. By age 25, Dg was 2.19 times as large at the 4.6-m spacing as at the 0.9-m spacing. Growth at the 2.7-m spacing was a little poorer in the 0.2-ha-plot trial than in the 49-tree-plot trial, relative to that at wider spacings.

For western redcedar, differences among the three widest spacings were slight, but there was a lot of variation among plots at the same spacing (table 2). Trees at the 0.9-m spacing grew more slowly than others since age 10, whereas growth at the 1.8-m spacing did not slow down until about age 15. At age 25, Dg was 2.41 times as large at the 4.6-m spacing as at the 0.9-m spacing.

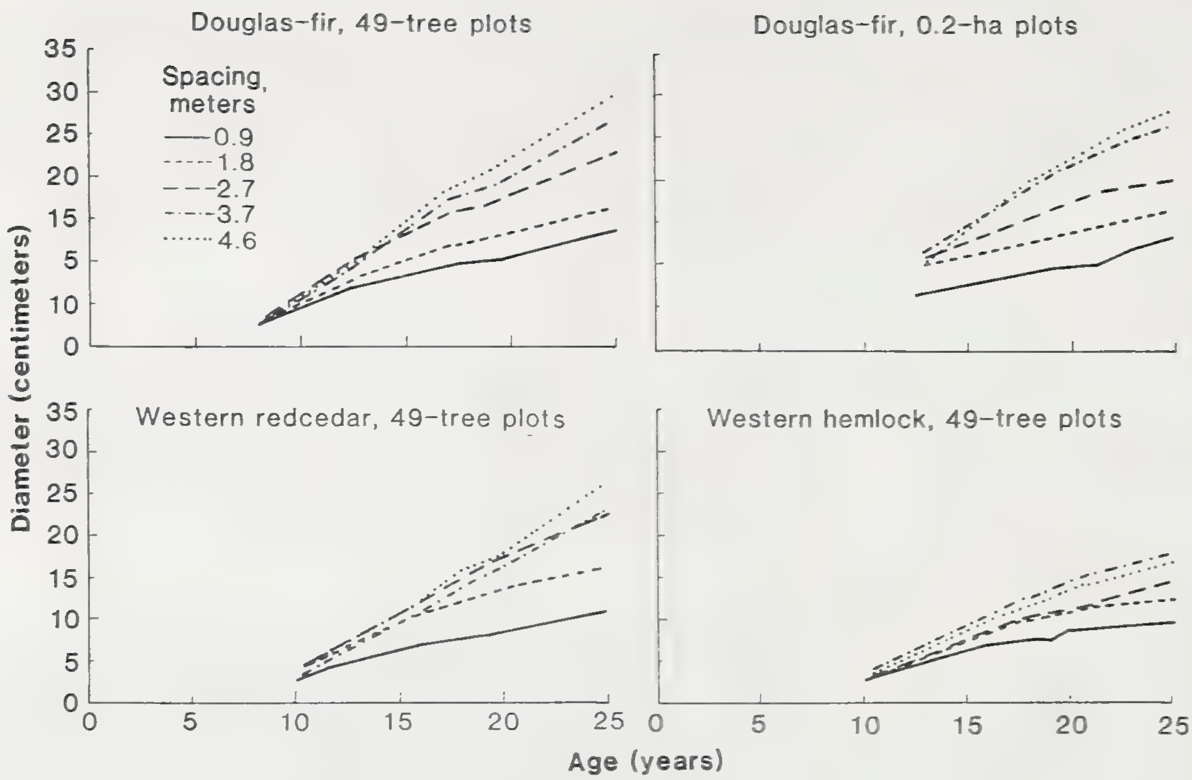

Figure 7a—Average d.b.h., by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

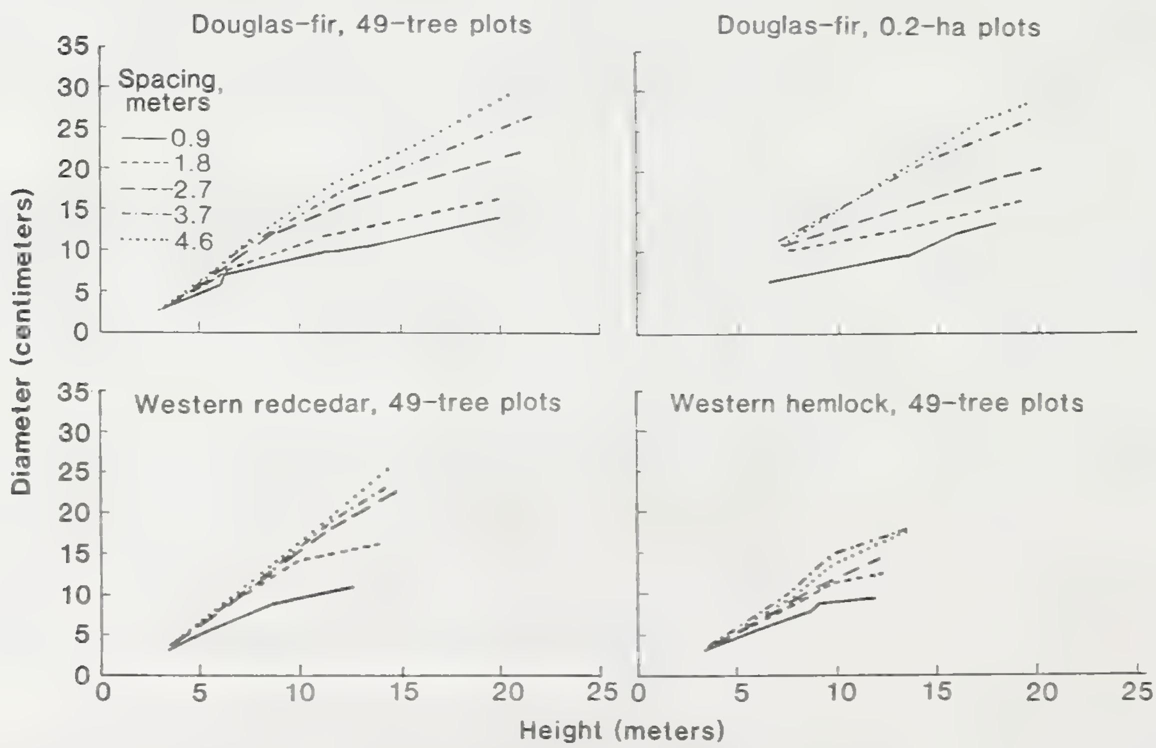

Figure 7b—Average d.b.h., by attained mean height and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

For western hemlock, there was much less difference among spacings. Clearly the trees at the 0.9-m spacing grew the least and those at the 3.7-m and 4.6-m spacings grew the most. Growth continued to slow down at the 0.9-m and 1.8-m spacings. At age 25, Dg was 1.88 times as large at the 3.7-m spacing as at the 0.9-m spacing.

At a common average tree height of 12 m, the ranges in d.b.h. for Douglas-fir (age 17-18), western redcedar (age 22-25), and western hemlock (age 23-25) were similar (fig. 7b). Trends over time (attained height) may differ among the three species, but irregularities make it impossible to attach any degree of certainty to apparent trends and differences therein. The graphs of d.b.h. as a function of height suggest that as long as trees are open grown, this relation is nearly linear; as each stand at successively wider spacing closes, the curve breaks away quite sharply. This pattern is illustrated most clearly for western redcedar.

Stem form — Stem taper is important to both tree quality and resistance of tree stems to breakage by wind or snow. Tall, slender trees are more likely to be broken. Europeans sometimes suggest that the ratio of height to d.b.h. (H-to-D ratio) of the 100 largest trees per ha, where height and d.b.h. are expressed in the same units, should be kept to less than about 80; the ratio for the average tree might then be up to about 100 (van Tuyll and Kramer 1981).

For all three species, H-to-D ratios at age 25 in the UBC trials were strongly influenced by spacing. At the 0.9-m spacing, trees were slender; average ratios ranged from 115 for cedar to 138 for Douglas-fir. At the 4.6-m spacing, tree boles tapered strongly; average ratios ranged from 56 for cedar to 75 for hemlock (table 2).

The H-to-D ratio apparently initially declined with increasing age (to about age 10-15) for all three species. Thereafter, for Douglas-fir the ratio leveled off at the two widest spacings, but increased at other spacings—more so at closer spacings. For cedar and hemlock, the ratio continued to decline at all except the closest spacing, but then increased between ages 20 and 25 at the 0.9- and 1.8-m spacings (fig. 8). We expect H-to-D ratios to continue to increase, as was also observed by van Tuyll and Kramer (1981).

Taper of the lower bole at age 25, as measured by the ratio of diameter at 2.7 m to d.b.h. apparently was nearly independent of spacing for Douglas-fir and for western hemlock (table 2). The ratio for redcedar was more irregular, but tended to decline with increased spacing; that is, taper increased with increased spacing because of butt swell.

Crown width — Generally, the wider the spacing, the wider the crown. Crown widths initially increased with increasing age (as tree size increased). This was followed by maintenance of a nearly constant crown width for Douglas-fir and hemlock; but crown widths of cedar apparently were still increasing at wide spacings at age 25 (fig. 9).

The curves for crown width have many irregularities that cannot be readily explained (fig. 9, a and b). Decreases could be real, but may not be; most irregularities are probably associated with sampling and measurement errors. Trends were not yet clearly established by age 25. Relative to height, instead of age, some irregularities are exaggerated.

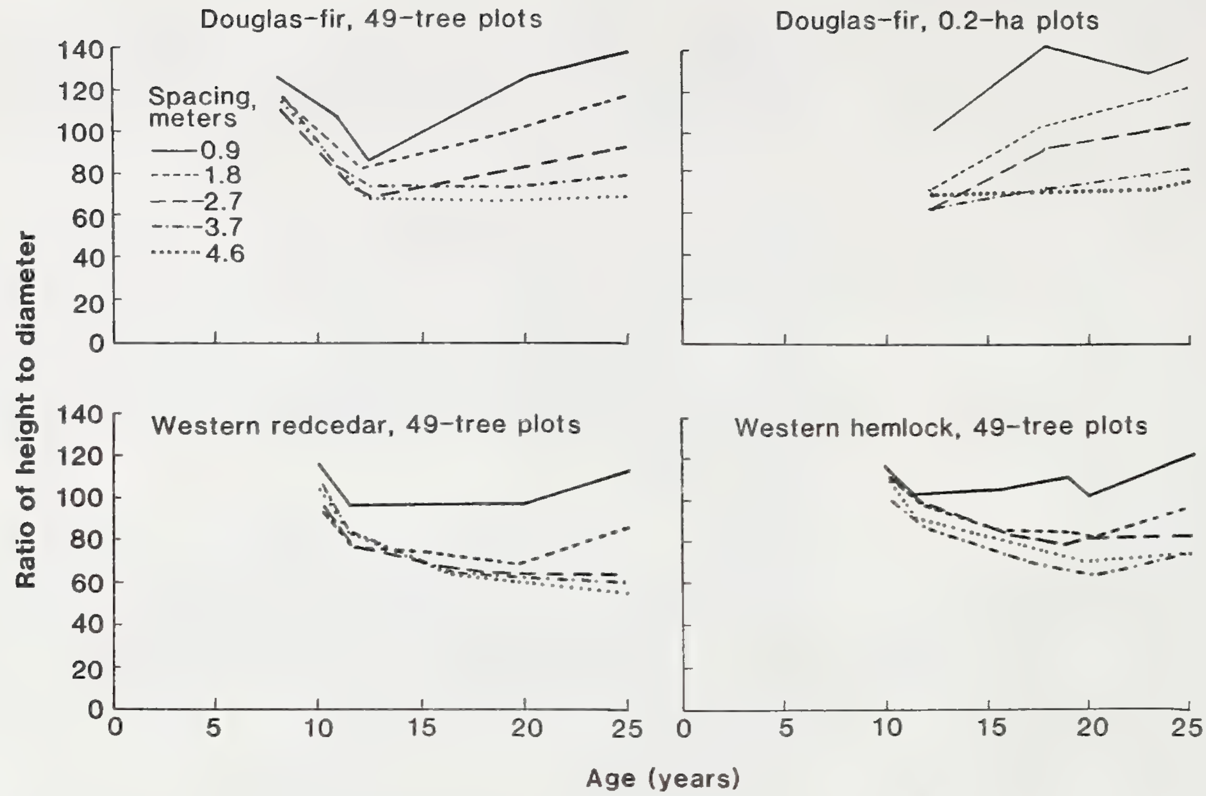

Figure 8—Ratio of height to d.b.h. (H-to-D ratio) for trees of average height and d.b.h., by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

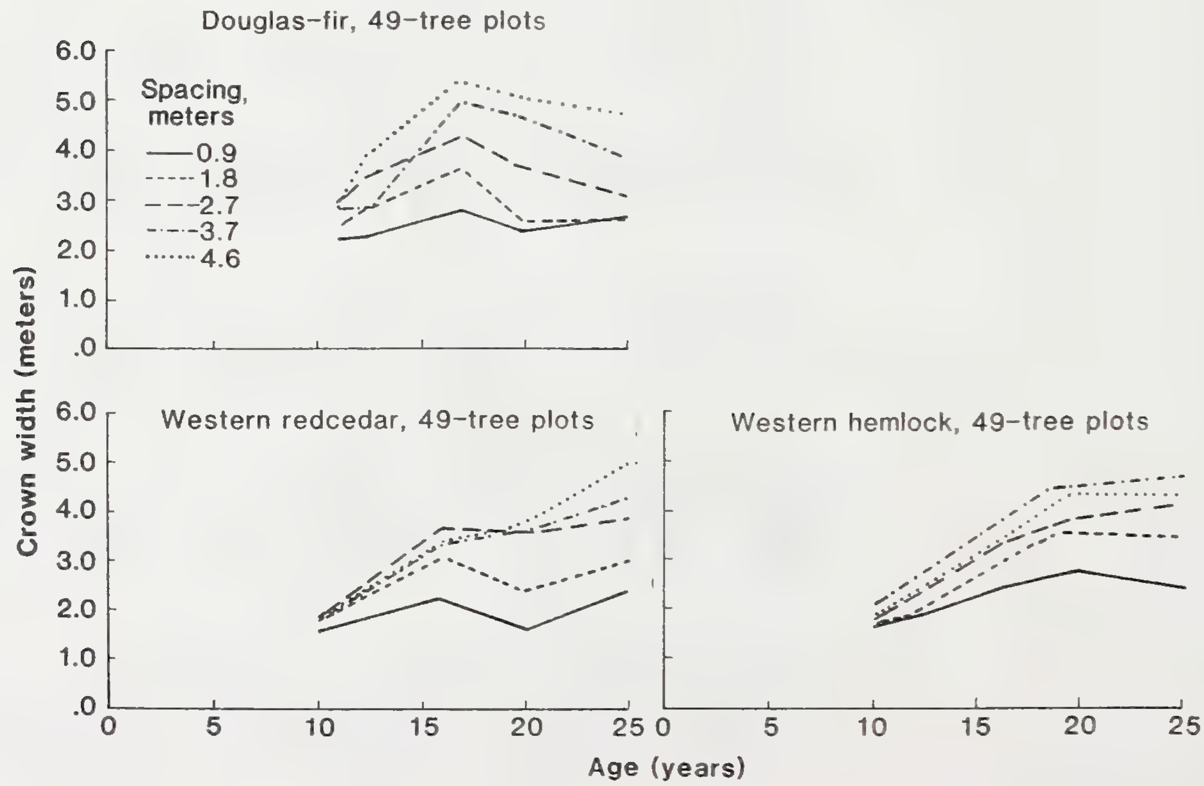

Figure 9a—Average crown width, by age and by spacing, for Douglas-fir, western redcedar, and western hemlock in the 49-tree-plot trial.

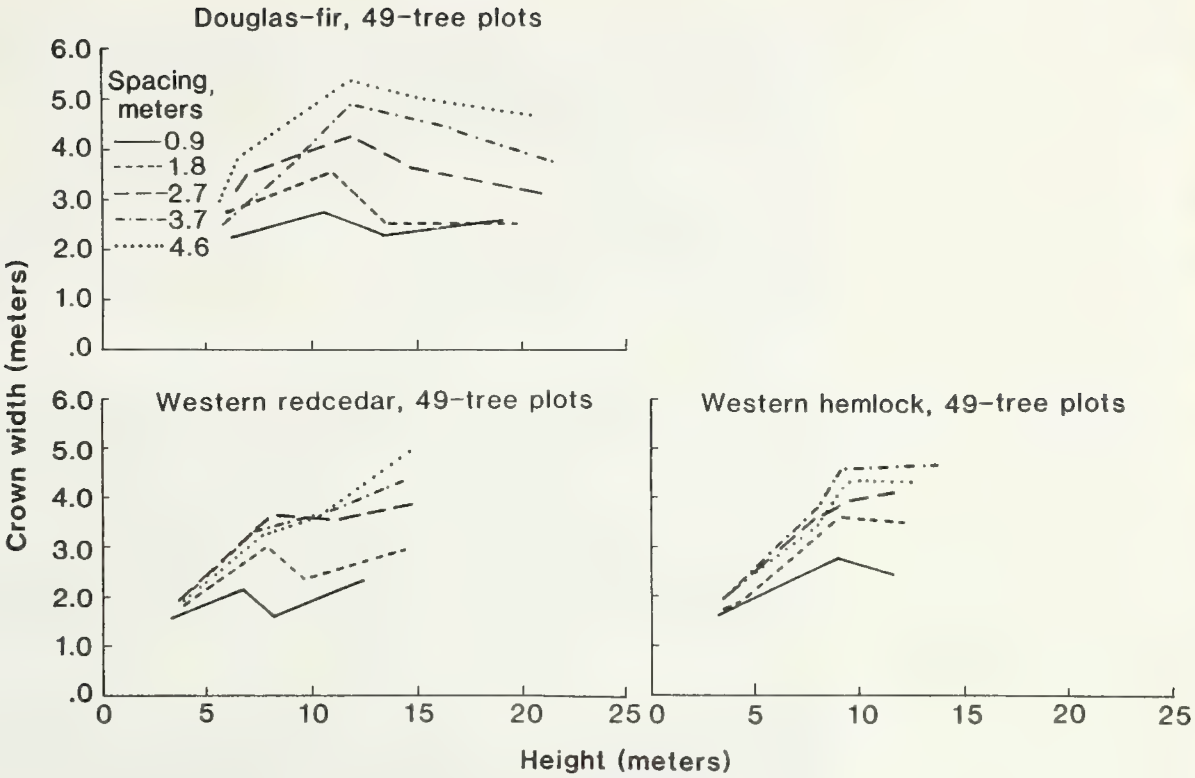

Figure 9b—Average crown width, by attained mean height and by spacing, for Douglas-fir, western redcedar, and western hemlock in the 49-tree-plot trial.

For all three species, the apparent maximum attained average crown width was consistently related to spacing:

Plantation spacing	Crown width, by species		
	Douglas-fir	Cedar	Hemlock
(m)	(m)	(m)	(m)
0.91	2.75	2.25	2.76
1.83	3.58	3.02	3.62
2.74	4.25	3.90	4.15
3.66	4.90	4.30	4.70
4.57	5.38	5.00	4.39

At the closer spacings, this maximum average crown width was much greater than the average distance between trees—a result of crown overlap. The ratio of maximum crown width to spacing declined with increased spacing in a curvilinear relationship. At the 0.9-m spacing, the maximum crown width of Douglas-fir and western hemlock was about three times the average spacing; at the 4.6-m spacing, the maximum average crown width of Douglas-fir was about 1.2 times the average spacing.

For Douglas-fir, this maximum crown width was apparently reached at about age 17 at all spacings, but the apparent difference between ages 17 and 20 may be a result of sampling error. The recent apparent increase in crown width at 0.9-m spacing could be associated with mortality of neighboring trees. For western redcedar, crown widths apparently were still increasing at age 25—at least at the two widest spacings. Crown widths differentiated by spacing in a manner similar to that for d.b.h. The indicated fluctuations possibly were "shrinkages" associated with rapid lifting of crowns. For western hemlock, this maximum crown width was apparently reached at about age 20 at all spacings.

Height to live crown and natural pruning — Height to live crown generally followed a consistent pattern. Crowns began to lift later with progressively wider spacing; once crowns began to lift, the rate of lift was similar at all spacings (fig. 10). Crowns lifted substantially on Douglas-fir, but very little on hemlock; cedar was intermediate. For Douglas-fir, the first log (6 m) was generally free of live branches at all spacings by age 25. For cedar, crowns lifted to 6 m only at the two closest spacings. Hemlock crowns barely started to lift.

At a common average tree height of about 12 m, the height to live crown at the 0.9-m spacing was just a little less for cedar than for Douglas-fir; it was much less for hemlock (fig. 10b). Heights to live crown at the three wider spacings, however, were much less for cedar than for Douglas-fir; cedar and hemlock were similar.

Douglas-fir crowns started to lift prior to age 12 and continued to lift quite rapidly. Among the three closest spacings, differences did not change much since age 12; that is, crowns at those spacings all lifted about 6 m between ages 12 and 25. At age 25, height to live crown averaged 4.7 m higher at the 0.9-m spacing than at the 4.7-m spacing. Western redcedar crowns at the 0.9-m spacing began to lift rapidly after age 16. Generally, the wider the spacing, the later and more slowly the crowns lifted. By age 25, average height to live crown was 3.8 m higher at the 0.9-m spacing than at 4.6-m spacing. For western hemlock, crowns at the 1.8-m to 4.6-m spacings lifted very little prior to age 20; between ages 20 and 25, they lifted a little more rapidly.

Natural pruning of Douglas-fir was slow and not greatly aided by close spacing because of the persistence of dead branches. Branches were not excessively large even at wide spacings; average diameter of branches at breast height increased from 1 to 3 cm over the range of spacings from 0.9 to 4.6 m. Dead branches persisted even at close spacings. Slower bole growth at close spacings reduced the advantage from somewhat more rapid self-pruning.

Crown length and crown ratio — Trends of crown length over time, derived as the difference between average tree height and average height to live crown, showed similarities but also substantial differences among the three species (fig. 11).

For Douglas-fir, crown length increased rapidly prior to age 20, with the rate of increase greater at wide spacings than at close spacings. Between ages 20 and 25, crown length apparently continued to increase at the 4.6-m spacing but tended to stabilize at all other spacings. Crown lengths at age 25 averaged 6 m (83 percent) longer at the 4.6-m spacing than at the 0.9-m spacing.

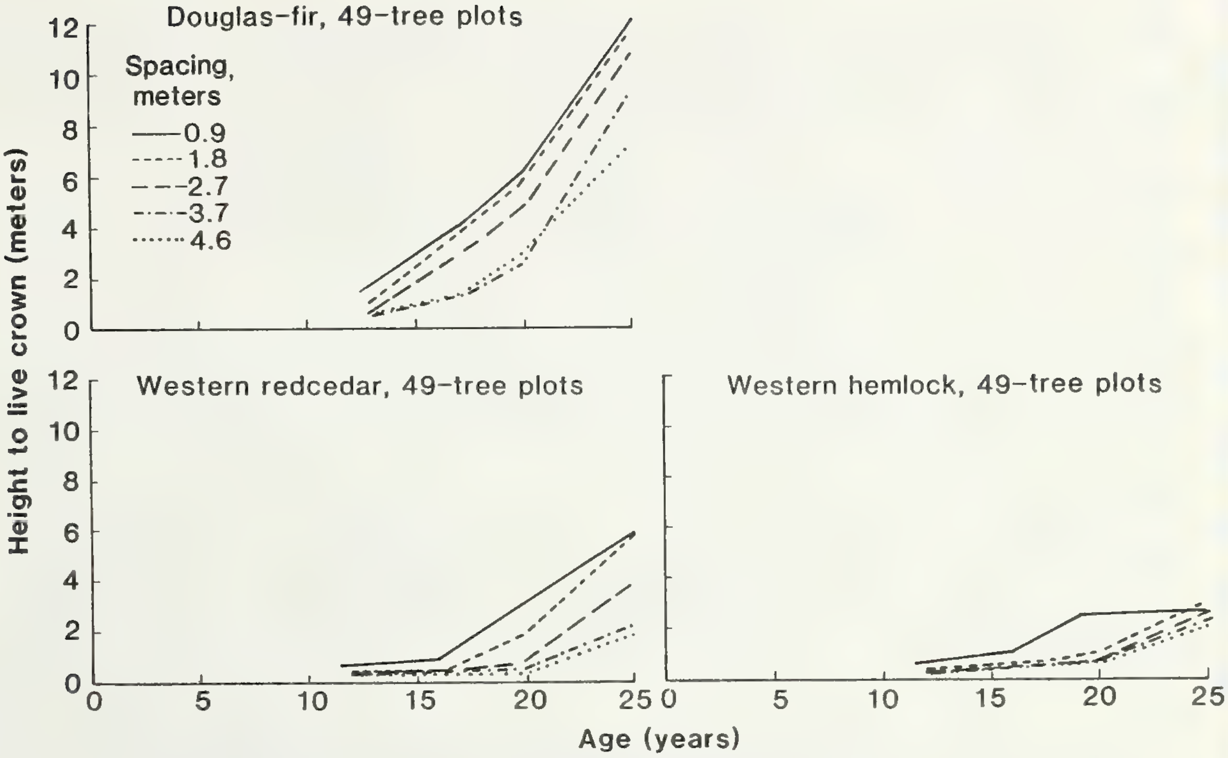

Figure 10a—Average height to live crown, by age and by spacing, for Douglas-fir, western redcedar, and western hemlock in the 49-tree-plot trial.

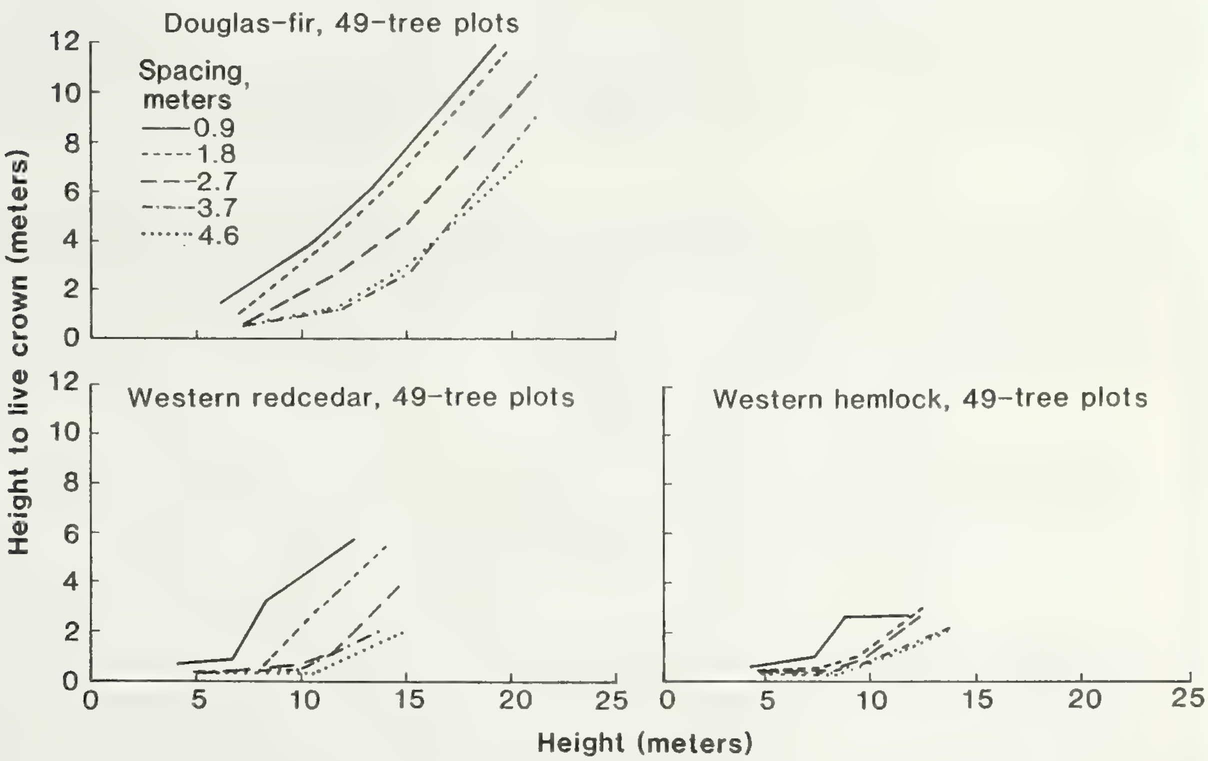

Figure 10b—Average height to live crown, by attained mean height and by spacing, for Douglas-fir, western redcedar, and western hemlock in the 49-tree-plot trial.

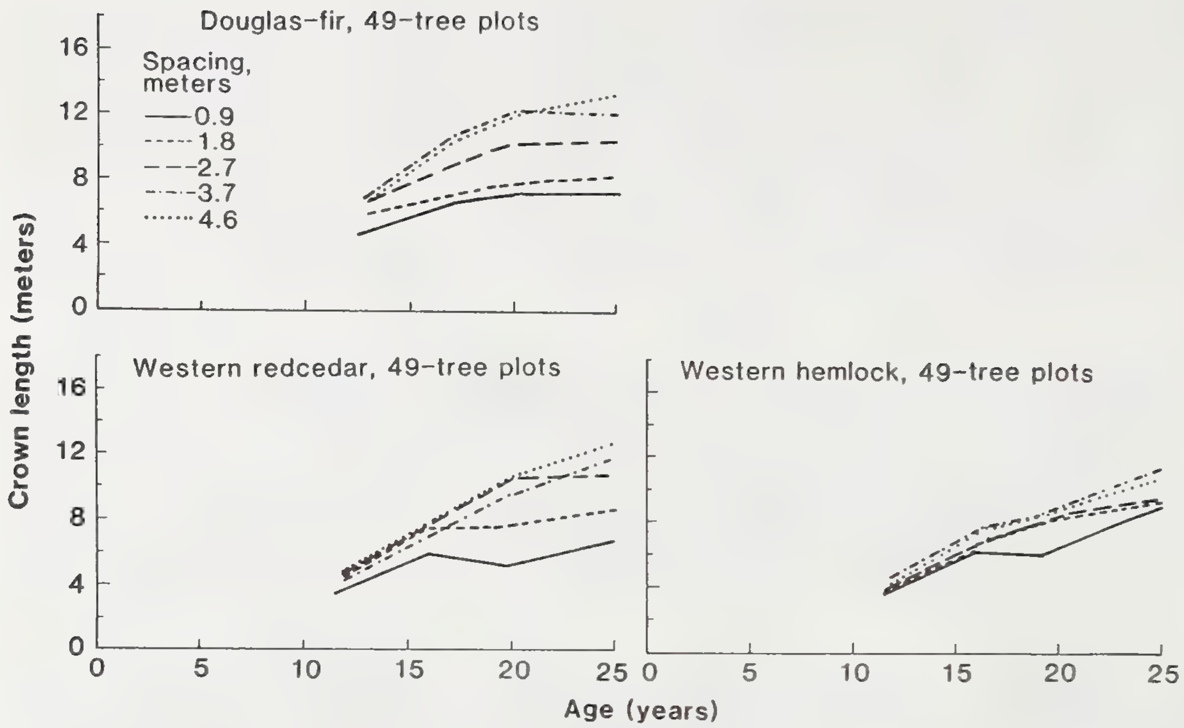

Figure 11—Crown length (derived as the difference between the average tree height and the average height to live crown), by age and by spacing, for Douglas-fir, western redcedar, and western hemlock in the 49-tree-plot trial.

For western redcedar, crown length continued to increase to age 25 at the 3.7- and 4.6-m spacings, but the rate of increase slowed down sharply after age 20 at the 2.7-m spacing and after age 16 at the 0.9- and 1.8-m spacings. Crown lengths at 25 averaged 6 m (88 percent) longer at the 4.6-m spacing than at the 0.9-m spacing.

For western hemlock, the rate of increase in crown length began slowing between ages 16 and 20, but crown lengths still increased substantially to age 25 at all spacings. Crowns were shorter at the 4.6-m spacing than at the 3.7-m spacing, which is consistent with other crown and stem dimensions. Hemlock exhibited much less range in crown length with spacing than did Douglas-fir and cedar.

At an average tree height of 12 m, the effect of spacing on crown length was least on hemlock (9.0 to 10.6 m) and greatest on cedar (6.5 to 11.5 m).

For both Douglas-fir and western redcedar, spacing had a substantial effect on the ratio of crown length to total height (crown ratio). For Douglas-fir at age 25, the average crown ratio ranged from about 38 percent at the 0.9-m spacing to 65 percent at the 4.6-m spacing (table 2). For western redcedar, it ranged from 54 (± 8) percent at the 0.9-m spacing to 86 percent at the 4.6-m spacing. For western hemlock, on the other hand, spacing apparently had very little effect on crown ratio. With the questionable exception of one plot at the 0.9-m spacing, the ratio at age 25 ranged from 73 to 86 percent.

Crown Shape — Some modelers have used crown shape, defined as the ratio of crown length to crown width (CL-to-CW ratio), as a way to estimate effects of spacing on crown development. Maguire (1984) used ratios of 1.9 for Douglas-fir and 2.2 for western hemlock. Two assumptions are that (1) crown shape is a constant for the species and (2) crown width is limited by spacing, such that lower branches do not continue to elongate once adjacent crowns touch. In reality, however, there is considerable intermingling of crowns, and definitions of both crown width and height to live crown may vary.

The CL-to-CW ratios in the UBC trials at age 25 averaged 3.1 for Douglas-fir and 2.7 for hemlock (table 2). The ratios appeared to be nearly independent of spacing for all three species. For Douglas-fir the ratio was slightly curvilinear with a peak at about the 2.7-m spacing, and for hemlock it appeared to be slightly greater at close spacings.

Survival and mortality — Trends in number of trees per hectare were consistent over time (fig. 12). Trends for the four wider spacings are more easily seen in terms of survival percentages (fig. 12b). The differences, among species and plots, in survival at the 0.9-m spacing account for most irregularities in the basal area and volume curves that are presented later.

Two aspects of mortality, in terms of number of trees lost, should be considered separately: (1) missing trees associated with planting failures—all losses prior to about age 10+, and (2) mortality that occurred subsequently—as competition started to become important at the closer spacings. We refer to these as "preestablishment" and "postestablishment" mortality. All preestablishment mortality was caused by factors unrelated to spacing; some preestablishment mortality represents unplantable spots (because of large stumps) rather than loss of planted seedlings. Some of the postestablishment mortality was also caused by factors unrelated to spacing, as opposed to self-thinning that was related to spacing, but causes cannot be separated.

Preestablishment mortality — Even after fill planting, losses of Douglas-fir prior to age 10 averaged nearly 10 percent in both the 49-tree-plot and the 0.2-ha-plot trials and varied irregularly with spacing. In the 49-tree-plot trial, losses varied from 5 percent at the 0.9-m spacing to 14 percent at the 1.8-m spacing. In the 0.2-ha-plot trial, losses to age 13 (excluding the 0.9-m spacing) varied from 5 percent at the 1.8-m spacing to 11 percent at the 3.7-m spacing; losses at the 0.9-m spacing were 5 percent at age 5.

Losses of western redcedar at age 5 averaged 10 percent and varied irregularly from 4 percent at the 0.9- and 4.6-m spacings to 17 percent at the 2.7-m spacing. Only at the 0.9-m spacing were any trees lost between ages 5 and 16.

Losses of western hemlock at age 5 averaged 13 percent and varied irregularly from 4 percent at the 2.7-m spacing to 23 percent at the 4.6-m spacing. Losses between ages 5 and 16 were the most irregular and varied from 0 at the 0.9- and 4.6-m spacings to 6 percent at the 1.8-m spacing. Thus, total losses to age 16 averaged 16 percent and varied irregularly from 8 percent at the 2.7-m spacing to 26 percent at the 1.8-m spacing. All losses before age 16 were undoubtedly related to conditions existing at the time of planting rather than to spacing.

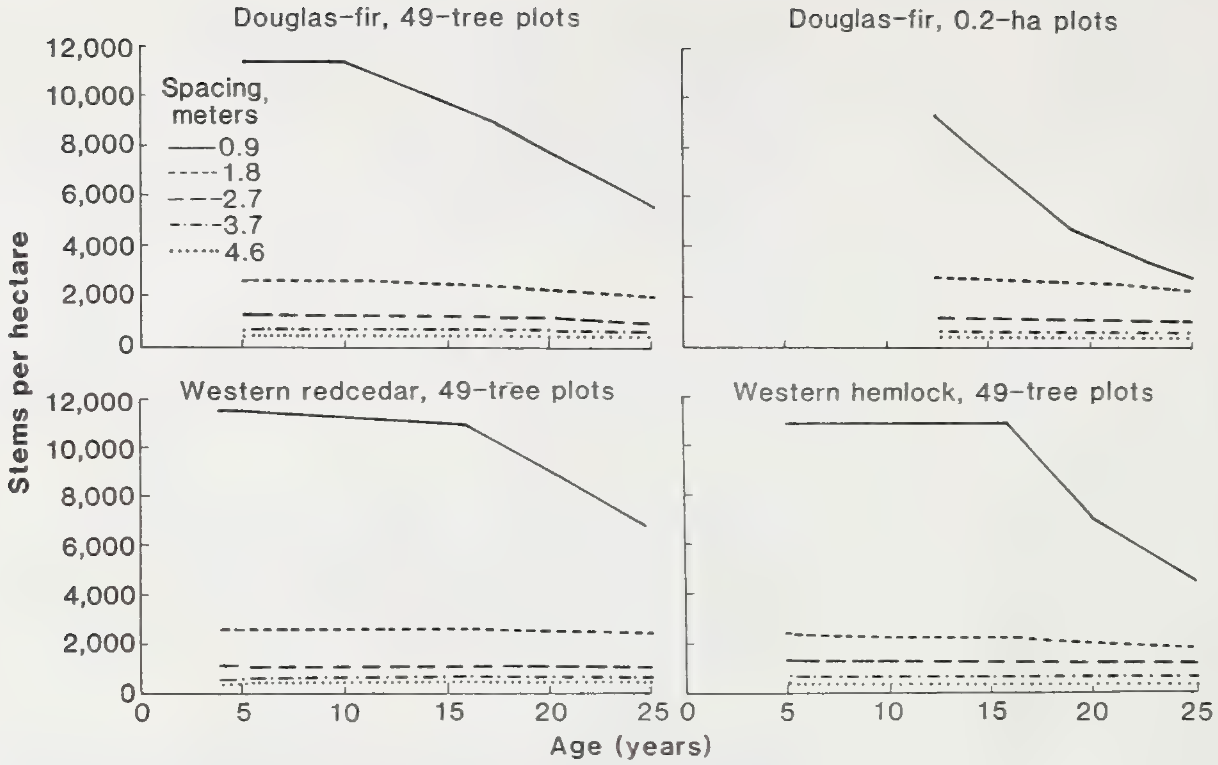

Figure 12a—Number of surviving trees per hectare, by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

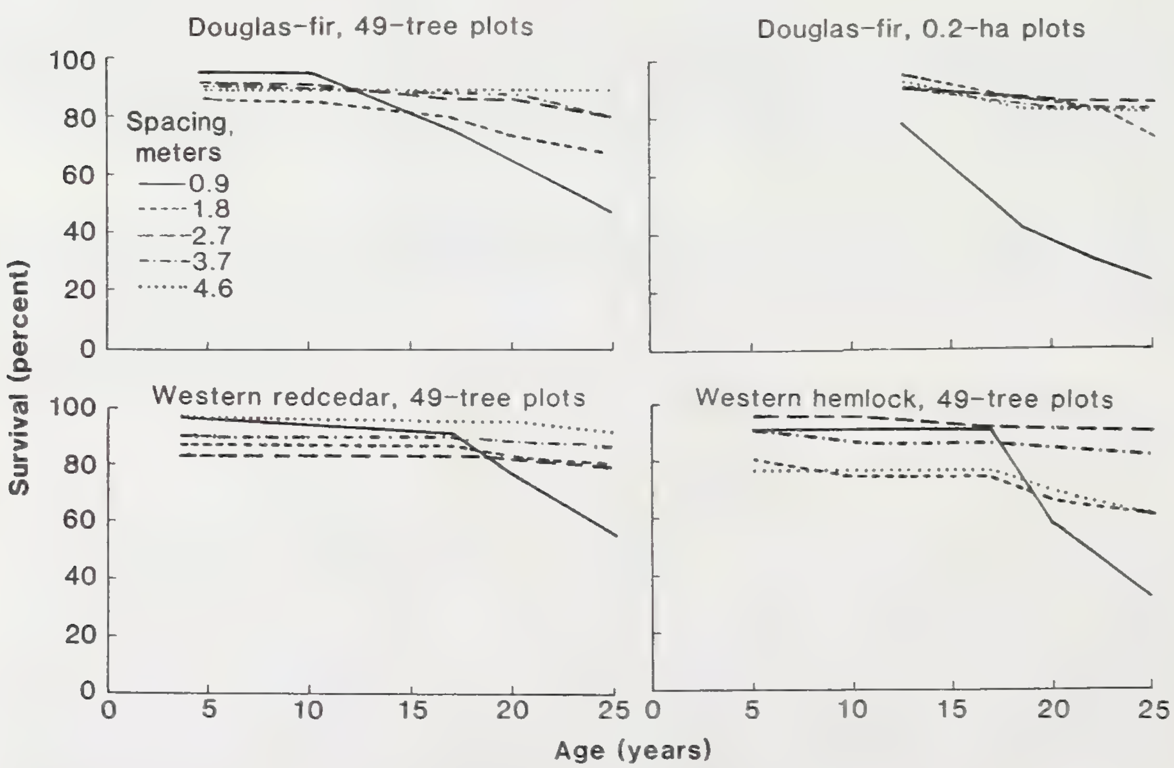

Figure 12b—Surviving trees as a percentage of the nominal number planted, by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

Postestablishment mortality — Substantial losses occurred at the 0.9-m spacing for all three species. Undoubtedly, these losses were mostly associated with intense competition and abnormal stand density. Substantial mortality at the 0.9-m spacing began later for both cedar and hemlock than for Douglas-fir; mortality apparently began when average tree height was about 5 m for Douglas-fir, 6 m for cedar, and 8 m for hemlock.

For all three species, and for both the 49-tree-plot and the 0.2-ha-plot trials for Douglas-fir, mortality after the stand became established was much greater at the 0.9-m spacing than at other spacings. Furthermore, Douglas-fir losses at the 0.9-m spacing were much greater in the 0.2-ha-plot trial than on the small plots in the 49-tree-plot trial because of snow press (fig. 12). By age 25, the 0.9-m spacing had lost about 43 percent more trees per ha in the 0.2-ha-plot trial than in the 49-tree-plot trial—76 vs. 53 percent of the theoretical number planted.

Losses at other spacings (1.8 to 3.6 m) were erratically distributed by spacing and mostly were not related to spacing; the losses tended to be a little greater at 1.8-m spacing, however. Recent Douglas-fir mortality was substantial at the 1.8-m spacing in both the 49-tree-plot and the 0.2-ha-plot trials. Losses between ages 10 and 25 in the 49-tree-plot trial were 20 percent at the 1.8-m spacing, 12 percent at the 2.7-m spacing, 11 percent at the 3.7-m spacing, and none at the 4.6-m spacing. Corresponding losses between ages 13 and 25 in the 0.2-ha-plot trial were 22, 5, 7, and 12 percent. Some of these losses were due to root rot.

Most self-thinning mortality occurred in suppressed and intermediate crown classes. Causes of mortality other than those related to level of competition (self-thinning and snow press) included damage by lesser vegetation and hardwoods, root rot, spots of heavily compacted soil, damage by squirrels (hemlock), deer browsing (cedar), and bud weevil (spruce).

Western redcedar mortality between ages 16 and 25 was light, even at the 1.8-m spacing: 7 percent at the 1.8-m spacing, 5 percent at the 2.7-m spacing, 3 percent at the 3.7-m spacing, and 4 percent at the 4.6-m spacing.

Western hemlock losses during this same period were 16 percent at the 1.8-m spacing, 1 percent at the 2.7-m spacing, 5 percent at the 3.7-m spacing, and 20 percent at the 4.6-m spacing. The substantial loss at the 1.8-m spacing may have been due mostly to competition. The heavy losses at the 4.6-m spacing, however, were due to other causes: One of the hemlock plots at the 4.6-m spacing is much drier and the other is much wetter than average; both mortality and growth rate were affected. Also, some of the hemlock mortality was associated with damage by squirrels.

Table 3—Average d.b.h. and basal area per hectare of the total stand and of the 500, 250, and 100 largest trees per hectare at age 25, by spacing, for Douglas-fir in the 0.2-ha-plot and 49-tree-plot trials and for western redcedar and western hemlock in the the 49-tree-plot trial[1]

Spacing	Number of surviving trees per hectare	Height 2/	Average d.b.h. of stand component: Total stand	500 largest	250 largest	100 largest	Basal Area of stand component: Total stand	500 largest	250 largest	100 largest
Meters		Meters	Centimeters				Square meters per hectare			
DOUGLAS-FIR, 0.2-HA-PLOT TRIAL										
0.9	2,898	17.8	13.4	20.1	22.0	24.5	40.8	15.8	9.5	4.7
1.8	2,213	19.5	16.7	23.0	24.9	26.9	48.7	20.7	12.2	5.7
2.7	1,128	20.2	20.6	24.7	26.8	29.2	37.5	24.0	14.1	6.7
3.7	619	19.9	27.0	28.6	31.4	34.4	35.4	32.1	19.4	9.3
4.6	392	19.4	29.4	--	32.6	35.8	26.6	--	20.9	10.1
DOUGLAS-FIR, 49-TREE-PLOT TRIAL										
.9	5,614	19.2	13.3	20.3	21.0	21.4	78.0	16.2	8.7	3.6
1.8	2,044	19.8	16.7	22.5	24.2	26.5	44.7	19.8	11.5	5.5
2.7	1,057	21.2	22.1	26.7	28.7	31.1	40.6	28.0	16.2	7.6
3.7	595	21.4	26.3	27.7	30.9	32.7	32.3	30.1	18.8	8.4
4.6	424	20.4	28.3	--	32.2	36.6	26.7	--	20.3	10.5
WESTERN REDCEDAR, 49-TREE-PLOT TRIAL										
.9	6,651	12.6	10.7	20.0	22.6	26.0	59.3	15.8	10.0	5.3
1.8	2,409	14.3	17.0	22.2	23.9	26.2	54.5	19.4	11.2	5.4
2.7	1,044	14.8	23.6	29.2	32.1	35.1	45.9	33.5	20.2	9.7
3.7	648	14.2	24.1	26.5	30.4	33.7	29.5	27.6	18.1	8.9
4.6	441	14.8	27.9	--	32.4	36.1	26.9	--	20.6	10.2
WESTERN HEMLOCK, 49-TREE-PLOT TRIAL										
.9	4,576	11.6	9.7	15.6	16.3	17.1	33.8	9.5	5.2	2.3
1.8	1,860	12.4	13.1	18.5	20.7	22.8	25.2	13.5	8.4	4.1
2.7	1,207	12.0	15.3	18.9	21.3	23.7	22.1	14.0	8.9	4.4
3.7	618	13.6	18.4	20.2	22.7	25.0	16.4	16.1	10.1	4.9
4.6	293	12.7	17.6	--	18.7	22.8	7.1	--	6.9	4.1

-- = not applicable.
1/ Via d.b.h.-distribution curves; average of 2 plots for the 49-tree plots.
2/ Average height of sample trees.

Diameter frequency distribution — All components of the stand benefited, in general, from increased spacing. This can be seen in the average d.b.h. of fixed numbers of largest trees (for example, the 250 largest per ha) (table 3) and in the percentage distribution of trees by d.b.h. class (for example, the largest 20 percent of the trees) (fig. 13). Complete diameter (d.b.h.) distributions, in number per hectare by 5-cm classes, are shown in table 4.

Table 3 indicates a strong increase in mean d.b.h. for all components of the largest trees over the full range of spacings from 0.9 to 4.6 m. For Douglas-fir there is a nice progression with spacing. Western redcedar falls in two groups, with the smaller trees in the 0.9- and 1.8-m spacings and the larger trees in the other spacings. Excepting the 4.6-m plots, which are on poorer sites, mean d.b.h. of the largest hemlock increases with spacing similarly to Douglas-fir. These data make it appear quite implausible that improved opportunities for selection, associated with close initial spacing, could compensate for the reduced growth that results from overcrowding in closely spaced stands.

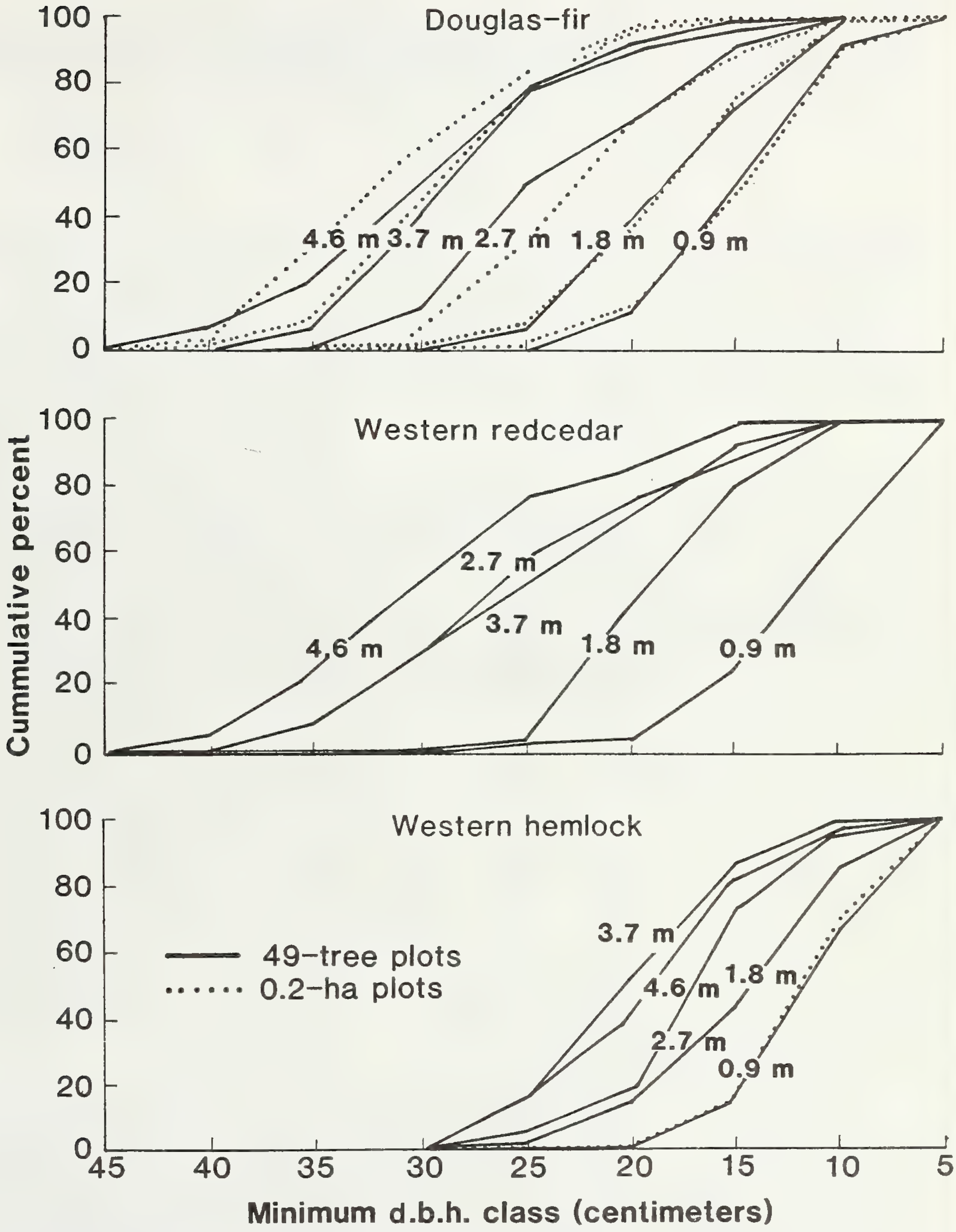

Figure 13—Distribution by percentage of trees at age 25, by minimum d.b.h. and by spacing, for Douglas-fir, western redcedar, and western hemlock.

Table 4—D.b.h. frequency distributions (number of trees per hectare) at age 25, by spacing, species, and d.b.h. class, for the 49-tree-plot and 0.2-ha-plot trials[1]

	Spacing and trial									
	0.9-m spacing		1.8-m spacing		2.7-m spacing		3.7-m spacing		4.6 m spacing	
D.b.h. class	49-tree plots	0.2-ha plots	49-tree plots	0.2-ha plots	49-tree plots	0.2 ha plots	49-tree plots	0.2-ha plots	49-tree plots	0.2-ha plots
Cm	Number per hectare									
					DOUGLAS-FIR					
5	488	283	30	14	--	9	--	--	--	--
10	2,319	1,274	519	515	81	112	23	8	5	--
15	2,136	961	671	891	244	228	38	17	29	12
20	671	319	702	594	203	406	69	104	54	52
25	--	51	92	176	393	303	221	212	122	88
30	--	10	30	23	122	70	198	224	122	124
35	--	--	--	--	14	--	46	42	63	100
40	--	--	--	--	--	--	--	12	24	16
							--	--	--	5
Totals	5,614	2,898	2,044	2,215	1,058	1,128	595	619	425	391
					WESTERN REDCEDAR					
5	2,380		30		--		--		--	
10	2,685		458		95		76		10	
15	1,342		854		203		84		54	
20	122		976		230		114		44	
25	122		61		217		191		103	
30	--		30		217		122		127	
35	--		--		68		61		83	
40	--		--		14		--		20	
Totals	6,651		2,410		1,044		648		439	
					WESTERN HEMLOCK					
5	1,586	1606	305		54		8		15	
10	2,258	2701	732		285		76		39	
15	732	787	549		637		206		117	
20	--	47	244		163		221		73	
25	--	--	30		68		107		49	
Totals	4,576	5,140	1,861		1,207		618		293	

-- = not applicable.

1/ Totals may not equal sum of column entries because all numbers are rounded to the nearest whole tree.

Percentage-of-frequency distributions at age 25 were similar in the 49-tree-plot and 0.2-ha-plot trials; this was especially true of both Douglas-fir and hemlock stands planted at the 0.9-m spacing (fig. 13). The greatest disparities between the 49-tree-plot and 0.2-ha-plot trials for Douglas-fir occurred at the 2.7- and 4.6-m spacings. The similarity of the percentage distribution for the 49-tree-plot and 0.2-ha-plot trials for Douglas-fir and western hemlock at the 0.9-m spacing suggests that loss of many trees due to snow press had little effect on relative diameter distribution but, instead, reduced the area actually occupied by the trees.

Shapes of cumulated d.b.h. distribution curves are generally consistent; there are a few incongruities, especially for cedar and hemlock. We believe deviations from the general patterns shown in figure 13 reflect variations in site or other factors unrelated to spacing; some merely reflect the irregularities associated with small sample sizes.

Basal area per hectare —For all three species, the wider the spacing the less the basal area per hectare. Differences among spacings widened initially but, for the four wider spacings, are now generally stabilized (fig. 14). The superiority of the 0.9-m spacing diminished as competition pressure reduced growth rates and increased mortality. Net growth at the 0.9-m spacing slowed markedly, while that at wide spacings apparently accelerated.

All per-hectare yield values (number of trees, basal area, total-stem volume, and merchantable volume) were strongly influenced by survival as well as by diameter; survival and diameter trends are presented together in figure 15. Diameters were influenced to a much lesser extent by variations in survival. A look at survival percentages reveals the reasons for irregularities in other stand parameters. Because some variation in survival was the result of factors unrelated to spacing and occurred irregularly over time, one must be careful in interpreting differences in basal area and volumes among species and plots.

The slowdown in net basal area growth of Douglas-fir after age 17 at the 0.9-m spacing in the 49-tree-plot trial was associated with a slight increase in rate of mortality (number per hectare) and a slight decrease in the rate of diameter growth. The lower level of basal area at age 18 at the 0.9-m spacing in the 0.2-ha-plot trial was associated with about one-half the number of trees per hectare present in the 49-tree-plot trial. Differences between the 49-tree-plot and the 0.2-ha-plot trials for other spacings were associated mostly with differences in **pre**establishment mortality, and to a lesser extent with differences in **post**establishment mortality and in rates of diameter growth.

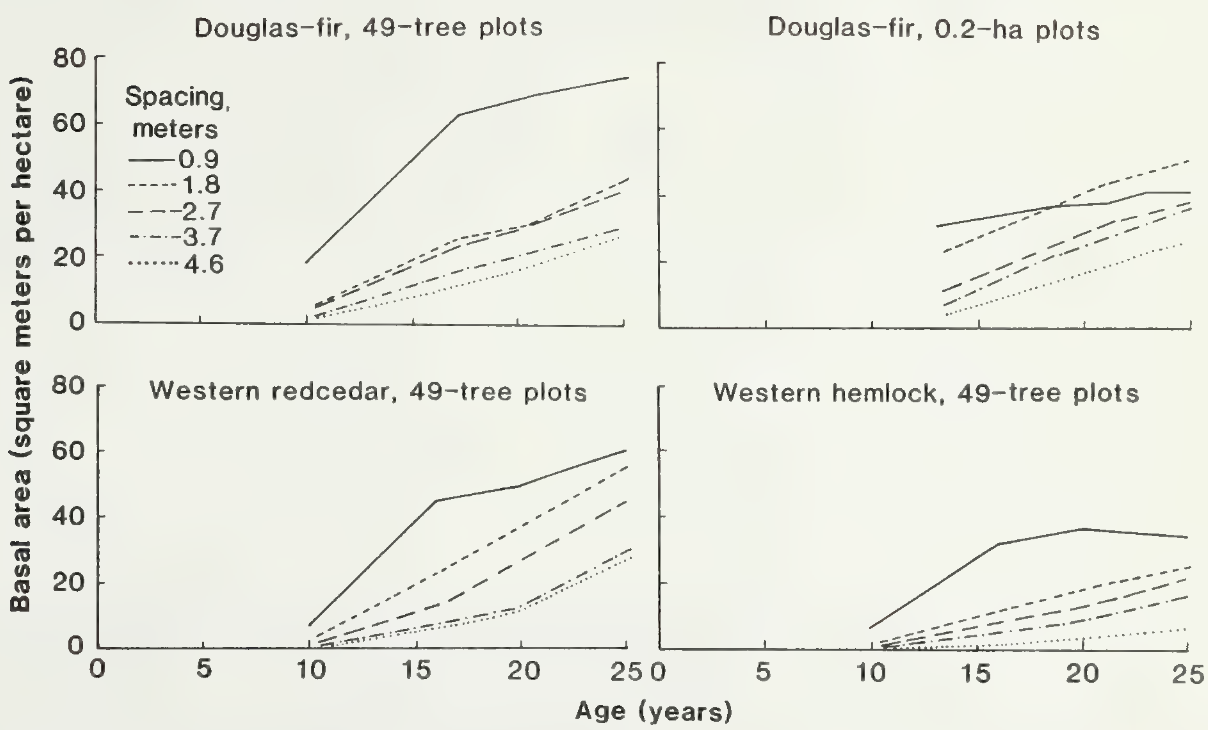

Figure 14—Basal area per hectare, by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

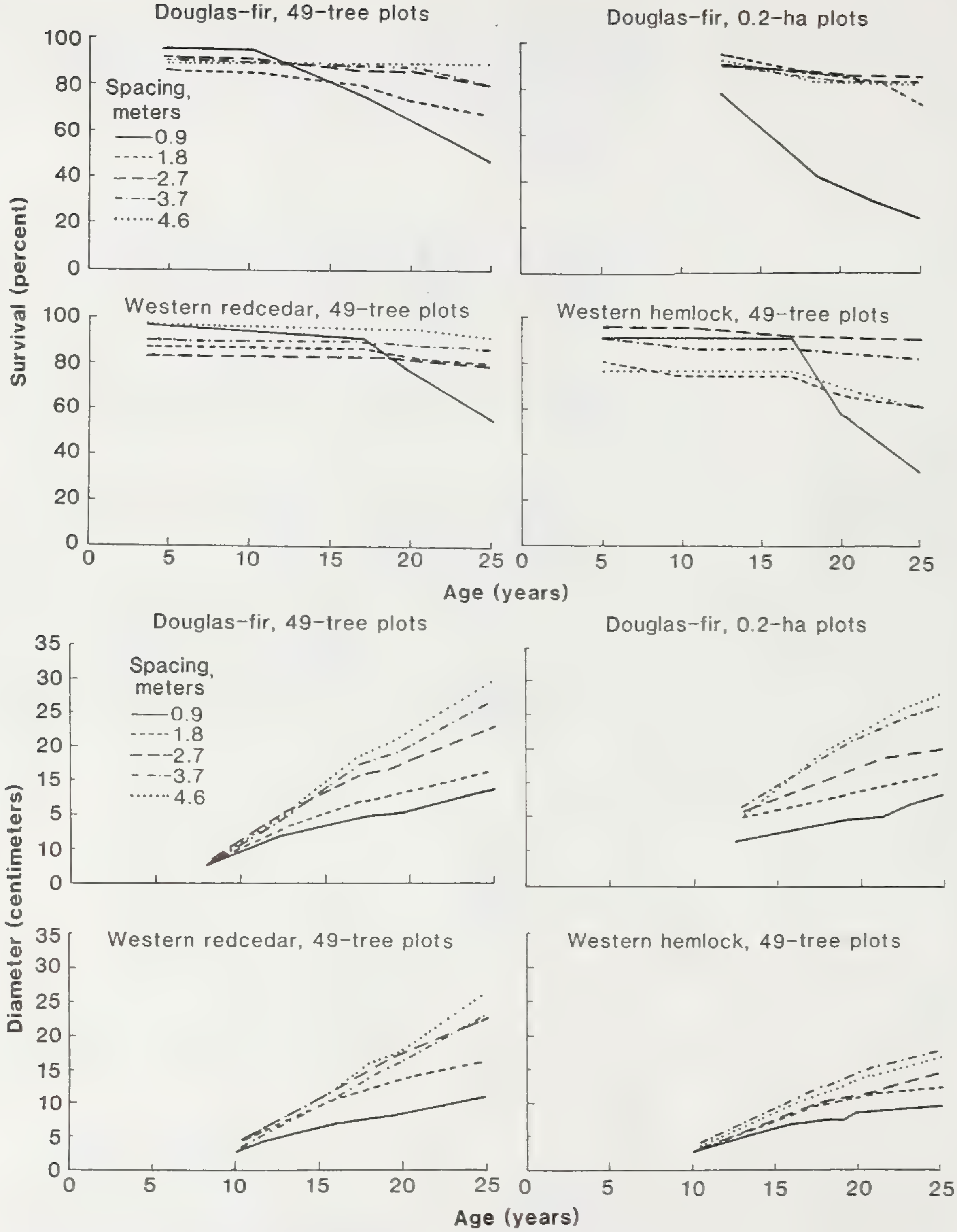

Figure 15—Survival percentage and average d.b.h., by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

For cedar and hemlock, the flattening of basal area curves for the 0.9-m spacing after age 16 was associated with rapid rates of mortality. The minor irregularity thereafter for cedar was associated with small differences in rates of both mortality and diameter growth, and that for hemlock was associated with substantial differences in rates of mortality. Trends for other spacings were associated with the number per hectare and average diameter.

Total-stem volume—Volume also decreased with increased spacing (fig. 16). For all three species, patterns of volume growth are quite similar to the basal area trends, except for exaggeration of the irregularity for cedar at the 0.9-m spacing and greater acceleration at the wider spacings with increasing age.

Net volume growth generally accelerated. For Douglas-fir, the rate steadily increased at all except the 0.9-m spacing; the rate of increase slowed markedly at the 0.9-m spacing, mostly because of heavy mortality. The trends for cedar were similar to those for Douglas-fir (except for the 0.9-m spacing, which reflects differences in mortality). For hemlock, stands at 1.8-m, 2.7-m, and 3.7-m spacings grew at about the same rate between ages 20 and 25; stands at the 4.6-m spacing grew more poorly, which was consistent with poorer crown development and heavy mortality.

Merchantable volume — Except for the 0.9-m spacing, trends for merchantable volume (cubic volume of the portion of the stem between a 30-cm stump height and a 10-cm top d.i.b. (diameter inside bark)) are similar to trends for total-stem volume (fig. 17). Trends shown for the 0.9-m spacing are different and, superficially, do not appear to be compatible with the other trends; merchantable volume did not begin to accumulate until much later at close spacings, but it then accumulated rapidly because of ingrowth.

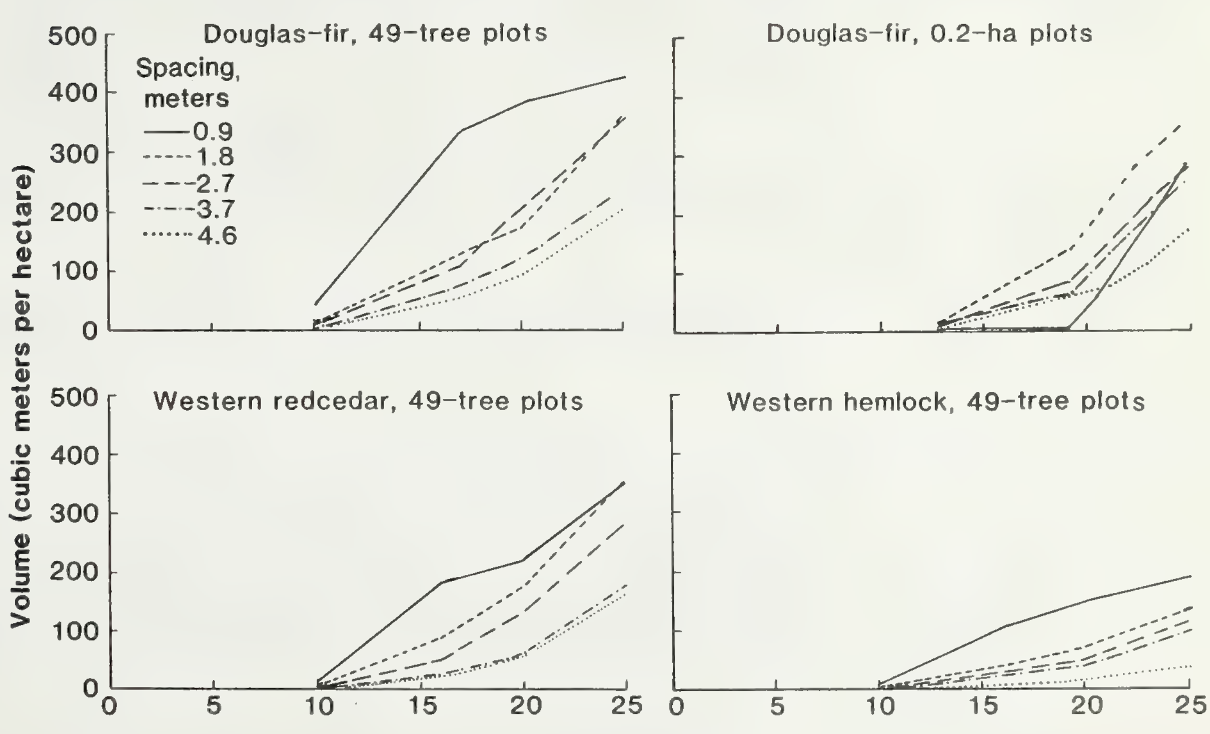

Figure 16—Total-stem cubic volume per hectare, by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

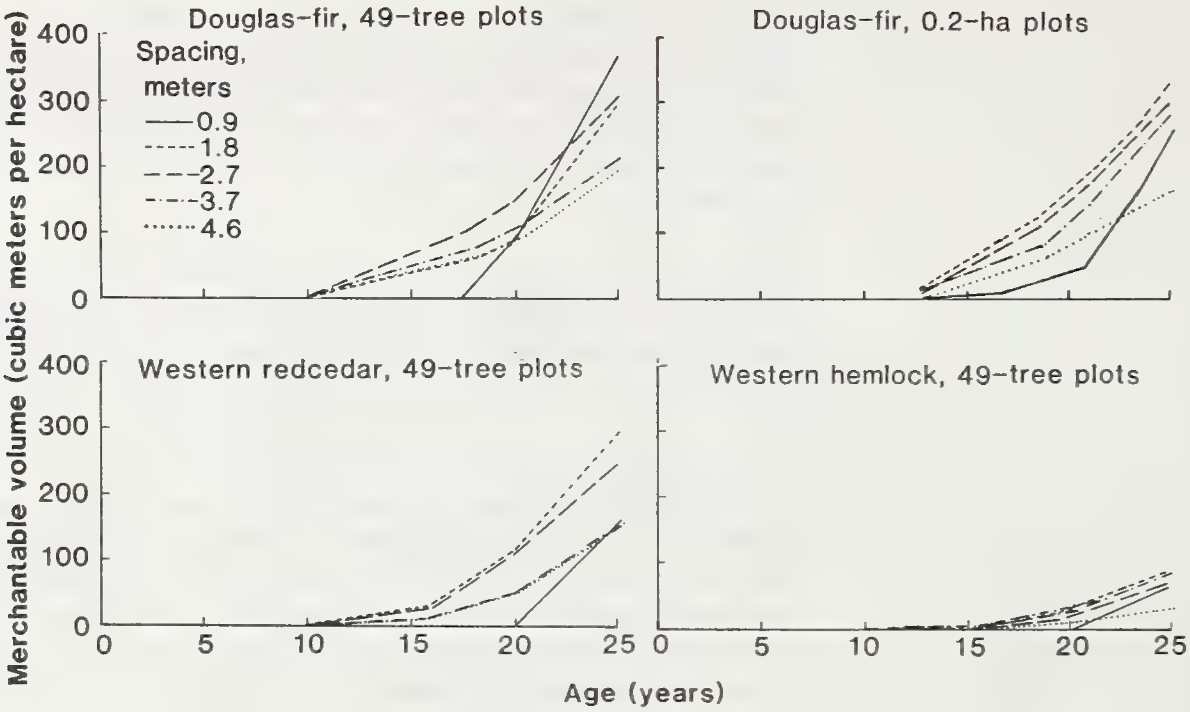

Figure 17—Merchantable cubic volume per hectare, by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial. Volume is for the portion of stem between a 30-cm stump height and a 10-cm top d.i.b.

The Rectangularity Trial

Survival and mortality — Early survival of trees planted in the rectangularity trial was generally rather poor. An average of more than 30 percent of the trees died by age 8. Dead seedlings were not replaced. On almost all plots, most early mortality was concentrated in patches; survival was good on portions of most plots. An aerial photograph taken in 1973 clearly showed many patches of mortality, which were quite large on some plots. Some of these patches left completely unoccupied areas and probably benefited the trees bordering them. In other cases, individual trees or small groups of trees were surrounded by large openings, which favored growth of these trees.

By looking at results from the 49-tree-plot and 0.2-ha-plot trials, one might expect that all mortality before age 8 was due to factors unrelated to spacing. The distribution of mortality, evident on the 1973 aerial photo, also supports this conclusion.

After age 8, heavy losses occurred in the pure Douglas-fir stands that were planted at the 0.9- and 1.4-m spacings. These losses were due mostly to snow press. At age 20, only 14 percent of the trees at the 0.9-m spacing and 26 percent of those at the 1.4-m spacing were still alive. Survival was better in the mixed than in the pure stands, perhaps because the irregular canopy reduced snow accumulations. At wider spacings, an average of 63 percent of the trees in the pure Douglas-fir stand survived, whereas 70 percent of the Douglas-fir and 58 percent of the hemlock in the mixed stand survived (table 5).

Table 5—Survival, mean d.b.h., and mean height at age 20 for the rectangularity trial, by spacing and by species

						Mixed stand					
			Pure Douglas-fir			Douglas-fir			Western hemlock		
Initial spacing	Treatment 1/	Initial 2/ number per hectare	Survival	D.b.h.	Height	Survival	D.b.h.	Height	Survival	D.b.h.	Height
Meters			Percent	Cm	Meters	Percent	Cm	Meters	Percent	Cm	Meters
0.9 by 0.9	UT	11,961	14	11.0	14.1	59	11.3	15.1	45	8.0	12.7
	1/3T	7,974	--	--	--	76	10.8	14.3	74	10.3	13.8
	1/2T	5,980	--	--	--	79	13.7	15.7	71	10.7	13.6
1.4 by 1.4	UT	5,316	26	12.1	14.7	69	13.3	16.7	66	12.9	14.8
	1/3T	3,544	--	--	--	83	18.4	18.7	33	13.8	14.8
	1/2T	2,658	--	--	--	72	17.9	17.9	72	12.9	15.6
1.8 by 1.8		2,990	70	14.2	15.1	86	17.6	16.2	67	13.4	15.2
1.8 by 2.7		1,994	83	15.6	15.8	58	19.8	15.6	39	13.4	12.6
1.8 by 3.7		1,495	64	18.9	16.2	60	19.8	15.4	52	14.0	12.7
2.7 by 2.7		1,329	56	19.5	15.6	69	20.6	14.9	61	17.1	15.7
2.7 by 3.7		997	49	19.2	14.2	80	21.9	16.0	72	16.3	13.5
2.7 by 4.6		797	53	21.6	15.4	79	23.7	16.2	49	18.8	15.5
2.7 by 5.5		665	64	21.3	15.3	61	22.9	16.0	57	16.2	12.9
Averages 1.8-m and wider spacings:			63		15.4	70		15.8	57		14.0

-- = not applicable.
1/ UT = unthinned; 1/3T = every 3d row cut; 1/2T = every 2d row cut.
2/ Nominal number per hectare planted or left after thinning at age 10.

In the mixed Douglas-fir/western hemlock stands, portions of plots planted at the 0.9- and 1.4-m spacings were thinned at age 10. Data for the unthinned third of each plot suggest that between ages 10 and 20 the stand at the 0.9-m spacing lost about 33 percent of its trees and the stand at the 1.4-m spacing lost about 16 percent. Apparent mortality in thinned portions varied, but was substantial in some instances; it was much less than in the unthinned portion at the 0.9-m spacing, but not at the 1.4-m spacing (table 6, a and b).

Height — At age 8, the average height of all trees was 3.3 m. Averages were virtually the same for both the pure Douglas-fir and the mixed Douglas-fir/western hemlock blocks, and for both species within the mixed block. Average heights on individual plots varied irregularly around this overall average—from 2.5 to 4.0 m for Douglas-fir and from 2.3 to 4.3 m for hemlock (fig. 18). In the mixed stand, Douglas-fir was taller than hemlock on six plots and hemlock was taller than Douglas-fir on three plots.

Over the next 12 years (to age 20), Douglas-fir consistently grew more than hemlock. The apparent increase in average height between ages 8 and 20 ranged from 11.0 to 15.5 m for Douglas-fir and from 9.7 to 12.8 m for western hemlock. There was no relation of height growth to either the spacing or the height at age 8. Heights at age 20 averaged 15.6 m for Douglas-fir and 14.0 m for hemlock (table 5). Variations around these averages were highly erratic and overshadowed any possible effects of spacing (fig. 18).

Table 6A—Apparent[1] cumulative mortality (percentage of nominal number planted or left after thinning), by initial spacing and by age, since time of *planting* on unthinned and thinned subplots in mixed Douglas-fir/hemlock stands in the rectangularity trial

Initial spacing	Treatment 2/	Douglas-fir, by age				Western hemlock, by age			
		10	11	17	20	10	11	17	20
Meters		Percent							
0.9 by 0.9	UT	15	18	30	41	31	31	41	55
0.9 by 0.9	1/3T	(13)	13	15	24	25	25	25	26
0.9 by 0.9	1/2T	(8)	8	17	21	(25)	(25)	25	29
1.4 by 1.4	UT	16	16	25	31	25	27	33	34
1.4 by 1.4	1/3T	(8)	(8)	8	17	58	63	63	67
1.4 by 1.4	1/2T	12	16	25	28	16	16	22	28

1/ Derived from numbers of surviving trees tallied at each age.
2/ UT = unthinned; 1/3T = every 3d row cut; 1/2T = every 2d row cut.

Table 6B—Apparent[1] cumulative mortality (percentage of actual number left after thinning at age 10), by initial spacing and by age, since time of *thinning* on unthinned and thinned subplots in mixed Douglas-fir/hemlock stands in the rectangularity trial

Initial Spacing	Treatment 2/	Douglas-fir, by age			Western hemlock, by age		
		11	17	20	11	17	20
Meters		Percent					
0.9 by 0.9	UT	3	17	31	0	15	35
0.9 by 0.9	1/3T	(0)	2	12	0	0	2
0.9 by 0.9	1/2T	(0)	10	15	(0)	(0)	5
1.4 by 1.4	UT	0	11	19	2	10	13
1.4 by 1.4	1/3T	(0)	(0)	9	10	10	20
1.4 by 1.4	1/2T	4	14	18	0	7	15

1/ Derived from numbers of surviving trees tallied at each age.
2/ UT = unthinned; 1/3T = every 3d row cut; 1/2T = every 2d row cut.

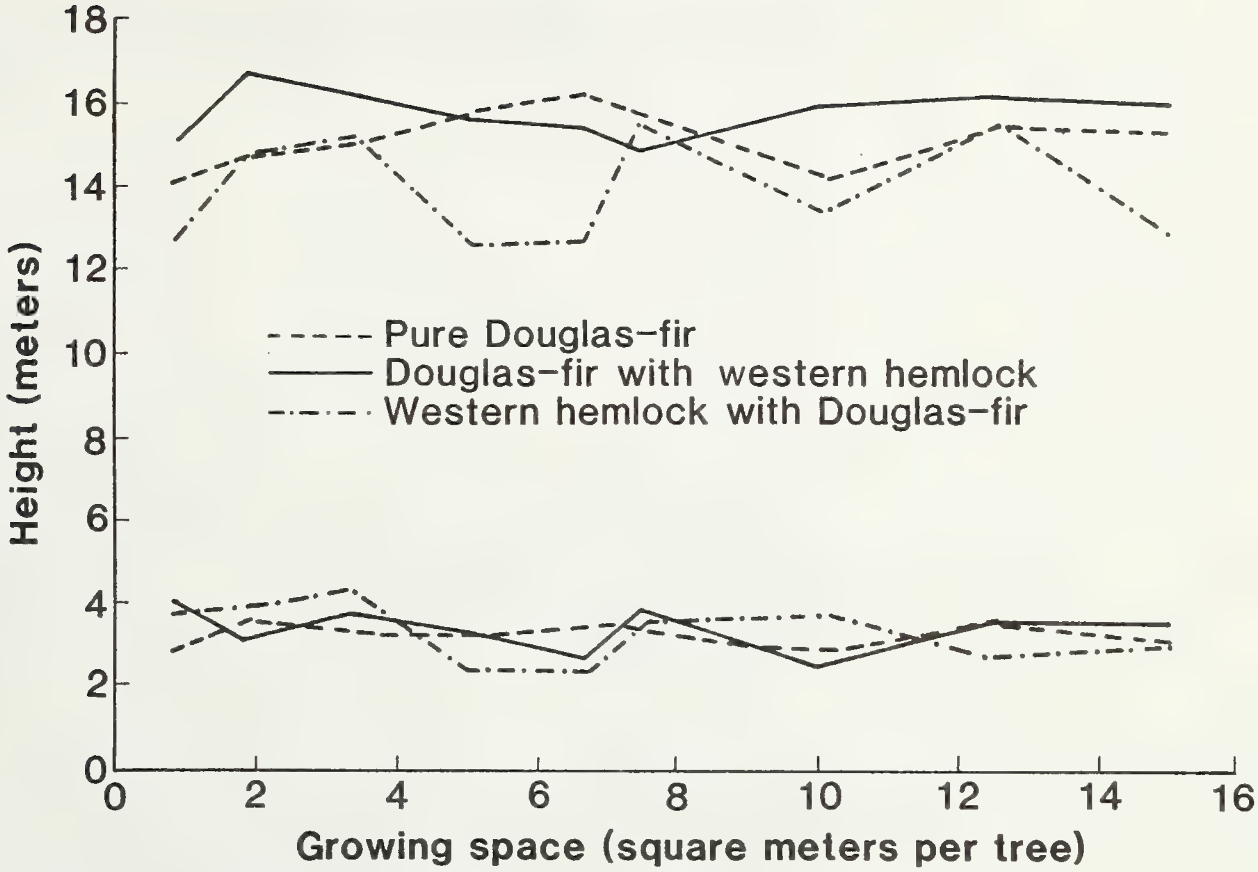

Figure 18—Average heights of Douglas-fir and western hemlock at ages 8 and 20, by nominal average growing space per tree, in the pure Douglas-fir and Douglas-fir/western hemlock blocks of the rectangularity trial.

In the mixed Douglas-fir/hemlock stands, attained height of Douglas-fir was taller than that of hemlock on all but one plot; the difference averaged 14 percent and ranged from -5 to 26 percent. These differences also bore no clear relation to spacing.

Average height of Douglas-fir, across all spacings, was 3 percent greater in the mixed stand than in the pure stand; at three spacings, however, Douglas-fir trees were shorter in the mixed than in the pure stands. Differences among plots were probably related primarily to site variation.

The heights of Douglas-fir in the rectangularity trial were a little greater (5 percent) than those at age 20 in the 49-tree-plot and 0.2-ha-plot trials, which averaged about 14.6 m. The heights of hemlock were much greater (49 percent) than those at age 20 in the 49-tree-plot trial, which averaged only about 9.4 m (table 7).

Table 7—Average height and the range of heights at age 20 for trees planted at spacings wider than 3 m² per tree, by species and by trial

Species and trial	Height: Average	Height: Range
	Meters	
Douglas-fir:		
49-tree plots	14.6	13.4-15.4
0.2-ha plots 1/	14.8	14.6-15.2
Rectangularity, pure	15.4	14.2-16.2
Rectangularity, with WH 2/	15.8	14.9-16.2
Nelder, pure	14.2	13.8-14.7
Nelder, mixed	14.4	13.5-15.0
Variable-block (age 22)	15.6	--
Western redcedar:		
49-tree plots	10.4	9.2-11.4
Nelder, mixed	6.6	4.8- 8.9
Variable-block (age 22)	5.7	--
Western hemlock:		
49-tree plots	9.4	8.9-10.1
Rectangularity, with DF 3/	14.0	12.6-15.7
Nelder, mixed	10.7	9.4-12.1
Variable-block (age 22)	13.5	13.1-13.9
Sitka spruce:		
Nelder, mixed	6.0	5.2- 6.8
Variable-block (age 22)	4.1	--

-- = not applicable.
1/ Interpolated between ages 19 and 23.
2/ With WH = grown with western hemlock in alternating rows.
3/ With DF = grown with Douglas-fir in alternating rows.

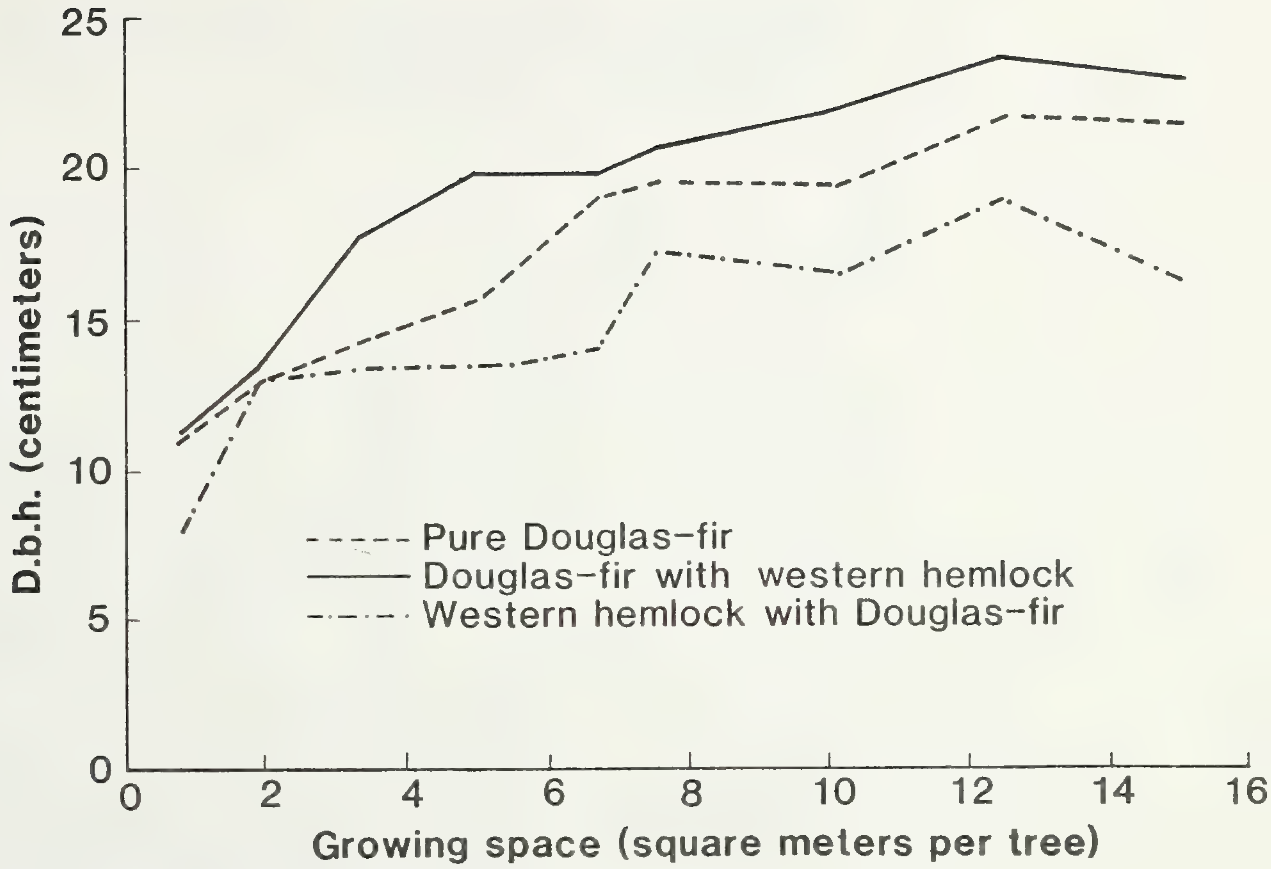

Figure 19—Average diameters of Douglas-fir and western hemlock at age 20, by nominal average growing space per tree, in the pure Douglas-fir and Douglas-fir/western hemlock blocks of the rectangularity trial.

Diameter — Average d.b.h. of Douglas-fir at age 20 increased strongly with increased spacing for spacings of 0.9 by 0.9 m through 2.7 by 1.8 m (table 5). Additional increase with progressively wider spacing was less and was somewhat erratic (fig. 19). In both the pure Douglas-fir stands and the mixed Douglas-fir/hemlock stands, the maximum average d.b.h. for both species occurred at the next to widest spacing (4.6 by 2.7 m). The slight falloff at the 5.5- by 2.7-m spacing was probably happenstance but might have been associated with heavy brush.

In the mixed Douglas-fir/western hemlock stands, the attained average d.b.h. of Douglas-fir was consistently greater than that of hemlock. Mean d.b.h. of Douglas-fir averaged 32 percent larger than that of hemlock; by plot, differences between the two species ranged up to 48 percent. These differences showed no relation to spacing (fig. 19).

Average d.b.h. of Douglas-fir at age 20 was consistently larger for a given plantation spacing in the mixed Douglas-fir/hemlock stands than in the pure Douglas-fir stands. This larger d.b.h. of Douglas-fir in the mixed stands, for a given nominal spacing, reflects the additional growing space available to Douglas-fir because of the slower growth (and poorer survival) of adjacent hemlock.

Average d.b.h. as a function of nominal growing space per tree in the pure Douglas-fir stands of the rectangularity trial was comparable with that in the 49-tree-plot and 0.2-ha-plot trials but was generally a little larger (table 8). Possible effects of spatial pattern were overshadowed by other sources of variation.

Table 8—Comparison among the five trials, and among species,[1] of height and average d.b.h at age 20, by spacing (or average growing space per tree)

A. 49-TREE-PLOT AND 0.2-HA-PLOT TRIALS

Spacing	Average growing space	DF, 49-tree		DF, 0.2-ha 2/		WRC, 49-tree		WH, 49-tree	
		Height	D.b.h.	Height	D.b.h.	Height	D.b.h.	Height	D.b.h.
meters	m²/tree	meters	cm	meters	cm	meters	cm	meters	cm
0.9 by 0.9	0.84	13.6	11.0	14.2	9.9	8.9	8.7	9.0	8.7
		13.2	10.2			7.6	8.0	9.1	7.8
1.8 by 1.8	3.35	13.7	13.0	14.6	14.0	9.3	13.7	9.4	11.1
		13.4	13.5			9.9	13.8	9.0	11.4
2.7 by 2.7	7.53	14.6	17.1	15.2	17.5	10.8	16.5	8.9	11.1
		15.3	18.7			11.4	18.4	9.6	11.4
3.7 by 3.7	13.38	15.2	21.0	14.7	21.8	9.2	13.9	9.5	13.7
		14.8	19.6			10.7	18.4	9.6	15.9
4.6 by 4.6	20.91	15.4	22.3	14.7	22.6	10.8	17.2	10.1	14.6
		14.6	22.6			10.8	18.6	9.3	12.7

B. RECTANGULARITY TRIAL

Spacing	Average growing space	Pure DF		DF w/WH		WH w/DF	
		Height	D.b.h.	Height	D.b.h.	Height	D.b.h.
meters	m²/tree	meters	cm	meters	cm	meters	cm
0.9 by 0.9	0.84	14.1	11.0	15.1	11.3	12.7	8.0
1.4 by 1.4	1.88	14.7	12.1	16.7	13.3	14.8	12.9
1.8 by 1.8	3.35	15.1	14.2	16.2	17.6	15.2	13.4
1.8 by 2.7	5.02	15.8	15.6	15.6	19.8	12.6	13.4
1.8 by 3.7	6.69	16.2	18.9	15.4	19.8	12.7	14.0
2.7 by 2.7	7.53	15.6	19.5	14.9	20.6	15.7	17.1
2.7 by 3.7	10.04	14.2	19.2	16.0	21.9	13.5	16.3
2.7 by 4.6	12.55	15.4	21.6	16.2	23.7	15.5	18.8
2.7 by 5.5	15.06	15.3	21.3	16.0	22.9	12.9	16.2

C. NELDER-PLOT TRIAL

Arc	Average growing space	DF, plot 1		DF, plot 2		WH, plot 2		WRC, plot 2		SS, plot 2	
		Height	D.b.h.	Height	D.b.h.	Height	D.b.h.	Height	D.b.h.	Height	D.b.h.
meters	m²/tree	meters	cm	meters	cm	meters	cm	meters	cm	meters	cm
1G 3/	--	13.1	11.3	15.1	17.2	12.5	10.5	4.4	3.5	5.8	6.7
2	0.83	13.4	10.1	14.5	15.6	10.1	8.7	3.4	4.1	6.3	6.4
3	1.08	13.0	9.7	13.5	12.5	10.5	9.2	5.2	5.0	6.9	8.9
4	1.35	13.0	9.2	14.6	13.0	10.1	10.6	7.2	7.2	7.0	8.6
5	1.72	12.9	10.9	13.3	12.8	13.1	17.1	5.4	5.5	6.5	8.3
6	2.13	13.2	10.6	14.8	16.2	10.7	9.0	6.5	6.9	6.0	8.2
7	2.82	13.3	11.5	14.8	16.2	12.2	13.0	7.7	10.6	6.9	12.5
8	3.57	14.5	14.2	14.7	18.0	11.6	13.5	6.0	11.5	6.6	10.7
9	4.54	14.4	14.0	15.0	19.6	11.7	14.9	7.2	9.7	6.6	12.7
10	5.76	14.7	15.8	14.4	19.7	9.4	12.2	6.8	9.1	6.8	14.8
11	7.34	13.9	16.0	14.7	21.2	9.4	12.1	8.9	13.3	6.2	12.4
12	9.30	13.8	16.8	14.3	20.0	10.7	14.9	7.2	9.3	6.0	14.7
13	11.83	14.2	19.0	14.4	23.0	12.1	17.6	6.1	9.7	6.0	12.8
14	15.21	14.3	20.4	14.1	22.3	9.5	14.5	4.8	7.1	5.5	13.7
15	19.27	14.4	21.3	14.7	23.8	10.2	14.1	5.1	5.9	5.3	11.1
16	24.40	14.0	20.9	13.5	21.3	11.5	16.0	7.4	10.7	5.2	11.8
17G 3/	--	14.0	20.2	14.7	25.1	10.6	14.4	7.4	10.6	5.8	12.0

D. VARIABLE-BLOCK TRIAL

Spacing	Average growing space	DF		WH		WRC		SS	
		Height	D.b.h.	Height	D.b.h.	Height	D.b.h.	Height	D.b.h.
meters	m²/tree	meters	cm	meters	cm	meters	cm	meters	cm
0.9 by 0.9	0.84	13.0	8.9	--	--	?	4.9	--	--
1.8 by 1.8	3.35	15.6	12.1	--	--	5.7	6.9	4.1	7.3
2.7 by 2.7	7.53	--	--	13.1	14.9	--	--	--	--
4.6 by 4.6	20.91	15.6	22.0	13.9	17.0	--	--	--	--

-- = not applicable.
? = not available.
1/ Species: DF = Douglas-fir, WRC = western redcedar, WH = western hemlock, SS = Sitka spruce; w/ means grown in mixture with.
2/ Interpolated between ages 19 and 23 for height on 0.2-ha plots.
3/ G = guard arc.

The effect on diameter growth of respacing stands at age 10 in those Douglas-fir/hemlock stands planted at the 0.9- and 1.4-m spacings was apparently about the same as if the stands had initially been planted at the spacings to which they were respaced. Responses differed somewhat erratically, however, by both initial spacing and species (fig. 20).

Stem form — For any given nominal spacing, western hemlock generally had the highest H-to-D ratio, and Douglas-fir in the mixed stand had the lowest. The ratios for Douglas-fir in the pure stand were intermediate, but generally were closer to those for Douglas-fir in the mixed stand. In general, the ratio declined (that is, stem taper increased) with increased growing space; the lower ratios for Douglas-fir in the mixed stand, relative to the pure stand, are consistent with this (fig. 21).

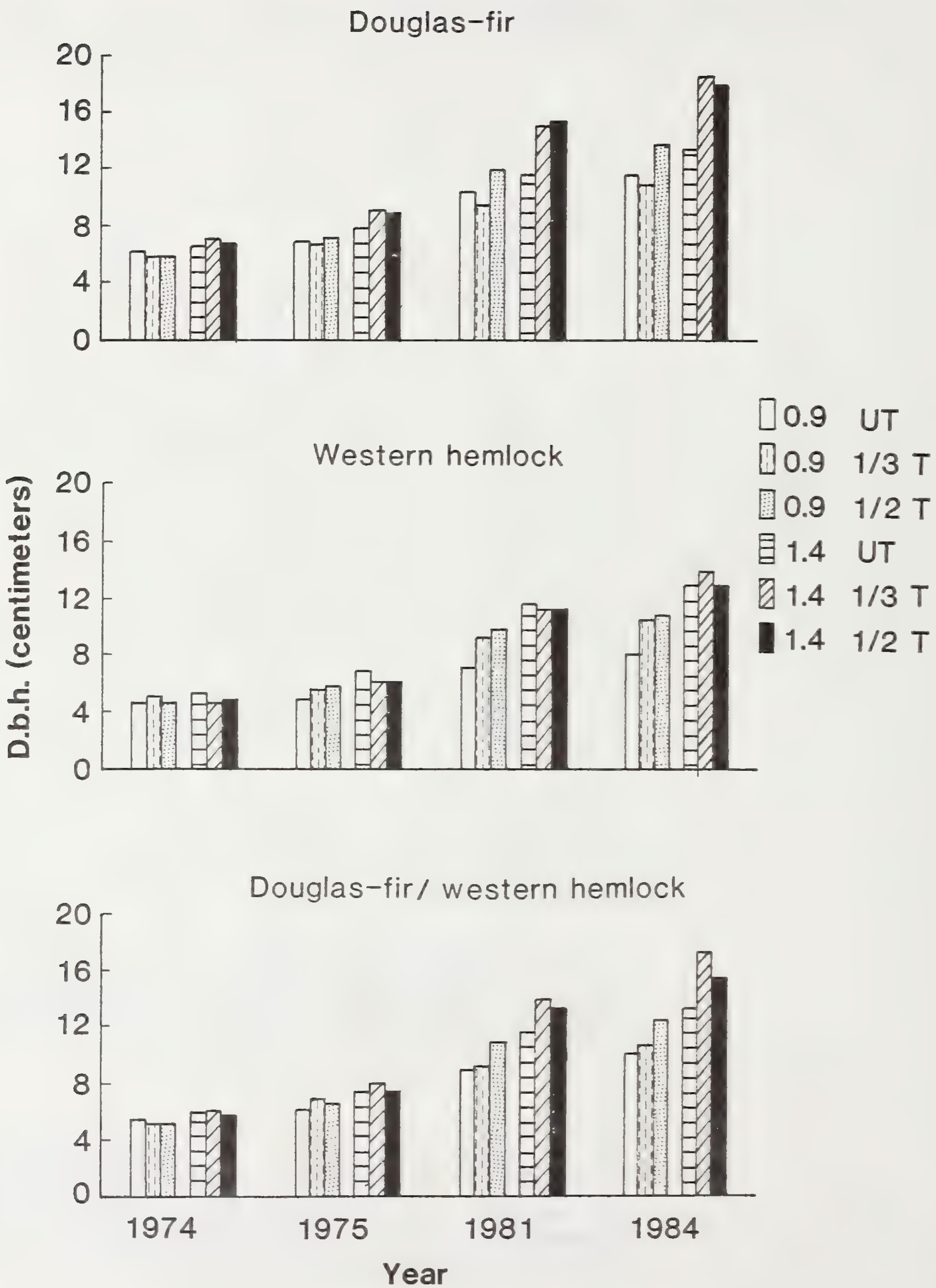

Figure 20—Average diameters of Douglas-fir, western hemlock, and the two species combined, by age and treatment (initial spacing and thinning), in the mixed Douglas-fir/western hemlock rectangularity trial plots that were thinned at age 10. UT = unthinned; 1/3 T = every third row cut; and 1/2 T = every second row cut.

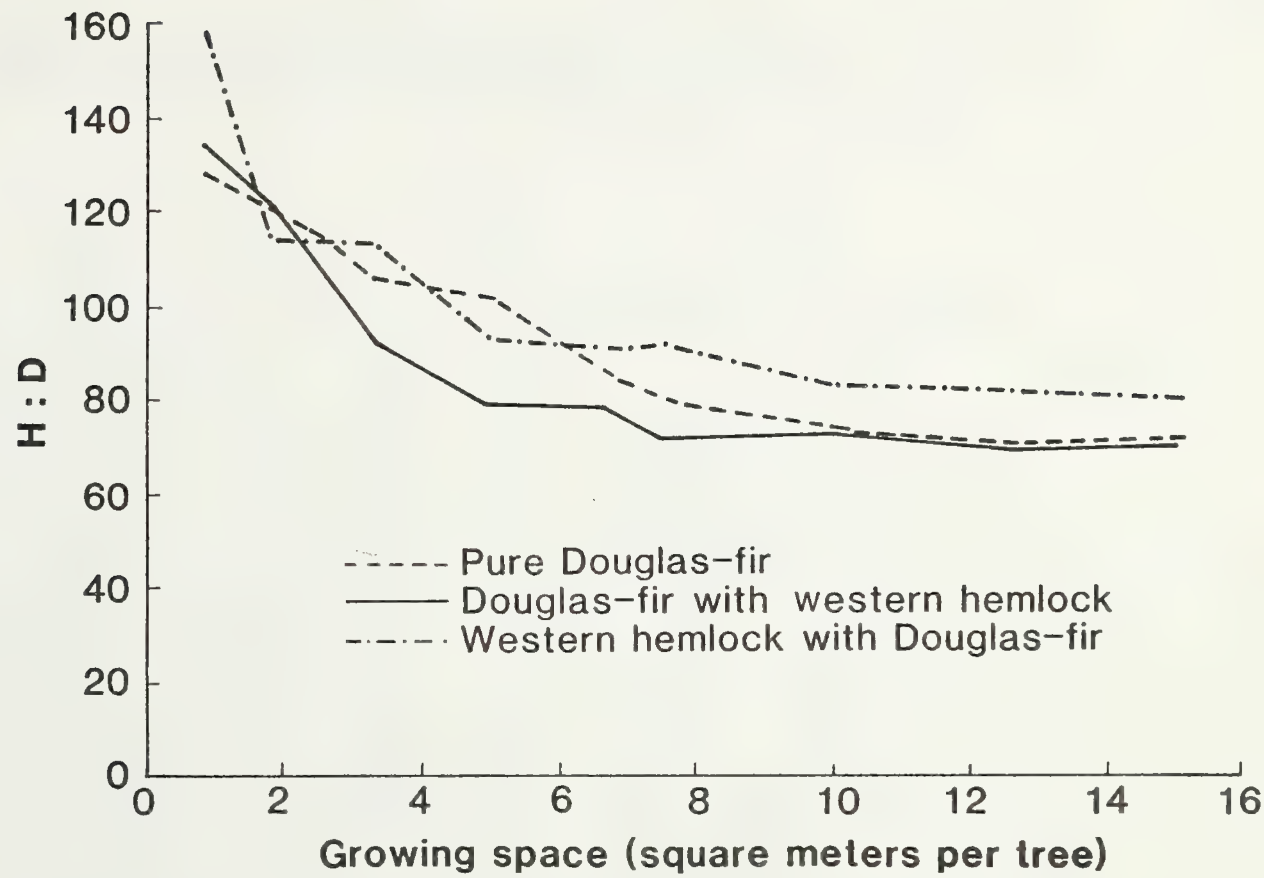

Figure 21—Ratio of height to d.b.h. (H:D) at age 20, for trees of average height and d.b.h., for pure Douglas-fir and for Douglas-fir and western hemlock grown in mixture in the rectangularity trial.

The Nelder-Plot Trial

Nelder-plot 1 (pure Douglas-fir) — Nelder-plot 1 showed clear trends of increased d.b.h. with increased spacing for spacings wider than about 1.5 m (table 9). Comparison of average annual d.b.h. growth for two successive periods, ages 11-15 and ages 15-20, showed that for spacings wider than about 1.5 m, differences in favor of the wider spacings increased over time at a substantial rate.

Nelder-plot 1 also showed depressed height growth at spacings of less than about 1.8 m; at spacings wider than this, however, height varied irregularly and showed no clear relation to spacing. Between ages 15 and 20, height growth became even more depressed at spacings of less than about 2 m; but there was no clear effect of spacing at spacings wider than 2 m.

The slightly greater growth, in both d.b.h. and height, on inner arcs may be associated with the position of those arcs near the "eye" of the plot; this suggests that a one-arc buffer is insufficient. Also, trees on arc 2 were cut on two of the three quadrants and those on arc 4 were cut on one quadrant in 1974. This cutting on arcs 2 and 4 released some trees on arcs 1, 3, and 5. Data shown for those latter three arcs therefore represent a combination of initial spacing effects and effects of release, and they are not comparable to data from other arcs.

Survival on this plot was excellent and averaged 93 percent (exclusive of arcs 2 and 4).

Table 9—Mean d.b.h. and height of Douglas-fir at age 20 and periodic annual growth between ages 11-15 and 15-20 in Nelder-plot 1 (spokes 1-36), by arc and spacing

			Age 20		Annual d.b.h. growth			Annual height growth		
Arc number	Spacing	Number of trees	D.b.h.	Height	Age 11-15	Age 15-20	Ratio	Age 11-15	Age 15-20	Ratio
	meters		cm	m	centimeters		percent	- - meters - -		percent
1G 1/	--	34	11.3	13.1	0.75	0.51	68	0.98	0.72	74
2	2/ 0.91	10	10.1	13.4	.65	.39	60	1.00	.84	84
3	1.04	33	9.7	13.0	.60	.38	64	1.00	.72	72
4	2/ 1.16	19	9.2	13.0	.58	.31	55	1.00	.70	70
5	1.31	30	10.9	12.9	.73	.40	55	1.00	.66	66
6	1.46	32	10.6	13.2	.75	.35	47	1.02	.74	72
7	1.68	32	11.5	13.3	.80	.39	49	1.00	.74	74
8	1.89	32	14.2	14.5	1.01	.63	63	1.15	.84	73
9	2.13	32	14.0	14.4	1.08	.60	55	1.05	.92	88
10	2.40	33	15.8	14.7	1.25	.81	65	1.12	.92	82
11	2.71	35	16.0	13.9	1.32	.84	63	1.05	.88	84
12	3.05	34	16.8	13.8	1.30	1.02	78	1.00	.88	88
13	3.44	35	19.0	14.2	1.53	1.19	78	1.10	.88	80
14	3.90	35	20.4	14.3	1.56	1.38	88	1.05	.88	84
15	4.39	35	21.2	14.4	1.68	1.55	92	1.08	.90	84
16	4.94	35	20.9	14.0	1.60	1.59	99	1.00	.92	92
17G 1/	--	33	20.2	14.0	1.59	1.48	93	1.00	.90	90

-- = not applicable.
1/ G = guard arc.
2/ Thinned in 1974 (age 12). On arc 2, trees were cut on two quadrants; on arc 4, trees were cut on one quadrant.

Spacings on arcs 8, 11, 13/14, and 15/16 are comparable to the four wider spacings tested on the 49-tree-plot and the 0.2-ha-plot trials. Spacing on arc 2 would be comparable to the narrowest spacing tested in those trials if arc 1 had provided a sufficient buffer around the "eye" (table 8).

Analyses of increment cores and branches from the rectangularity component of Nelder-plot 1 showed no harmful effects of rectangularities up to 4:1 (6 m by 1.5 m) on boles to age 20.

Nelder-plot 2 (four species) — In Nelder-plot 2, Douglas-fir consistently grew the best, hemlock a distant second, spruce third, and cedar the poorest. Survival of Douglas-fir and Sitka spruce were quite good at 89 and 95 percent, respectively; however, survival of cedar and hemlock were poor at 60 and 44 percent, respectively. Because of this poor survival, the effective space available to many trees was much greater than that implied by the original plantation spacing.

As in Nelder plot 1 and the other trials, d.b.h. of Douglas-fir increased strongly with increased spacing (fig. 22). (Growth of trees on inner arcs benefited from the wide opening around the single tree in the center of the "eye.") On all arcs of Nelder-plot 2, trees attained a much larger average size than on the equivalent arcs in Nelder-plot 1 (fig. 23). Of the three contiguous rows of Douglas-fir, one always borders on hemlock and one on cedar. Because these latter two species grew so much more poorly than Douglas-fir, and had poor survival, the Douglas-fir trees had much more available growing space than trees on the equivalent arc in Nelder-plot 1. It is apparent to one who looks down the rows that the trees in the rows bordering on cedar or hemlock are larger than trees in the middle row, especially at the closer spacings.

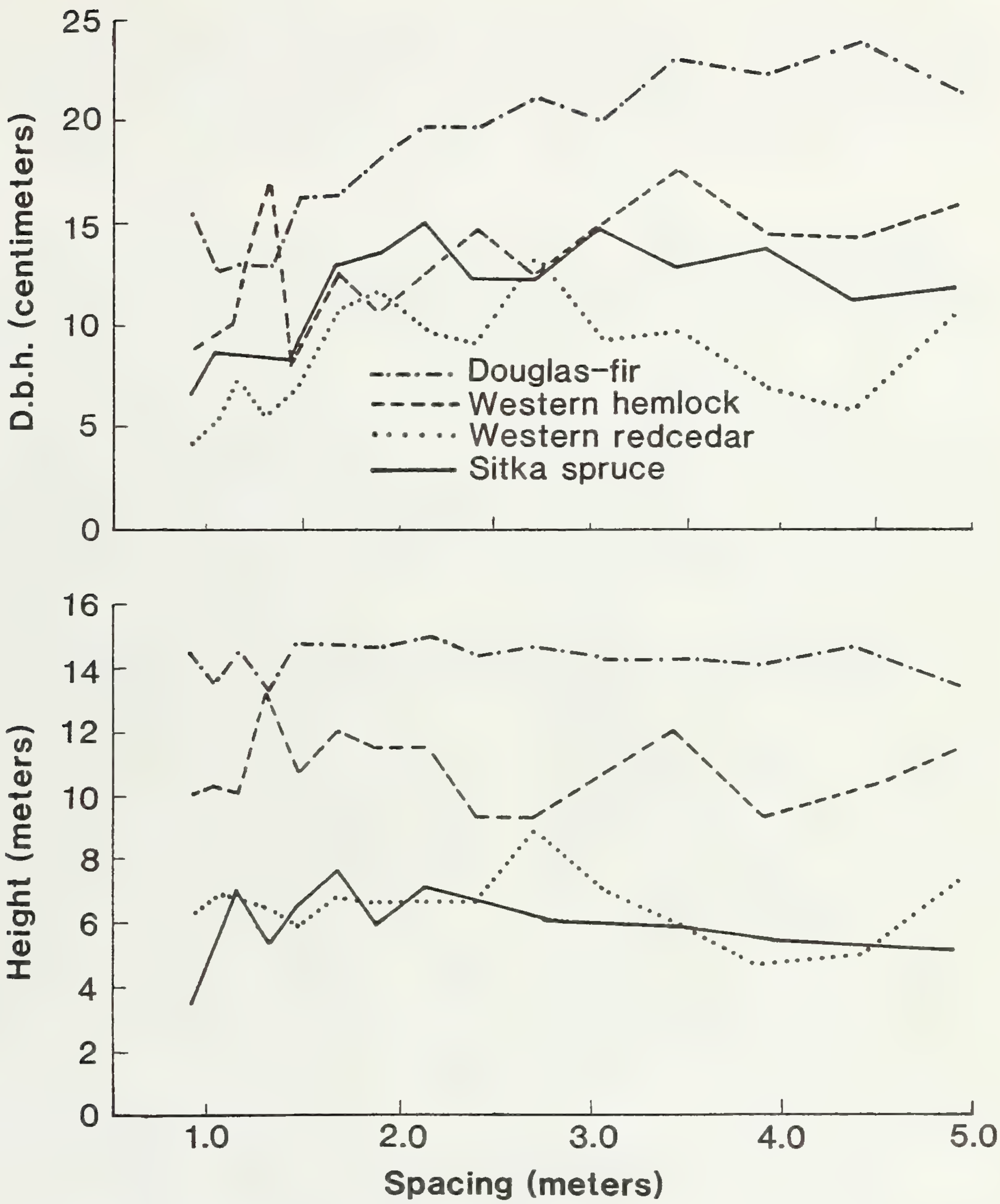

Figure 22—Average d.b.h. and height of Douglas-fir, western redcedar, western hemlock, and Sitka spruce at age 20, by spacing, in Nelder-plot 2.

Attained size of the other three species, unlike Douglas-fir, at age 20 did not bear such a strong relation to planted spacing (fig. 22). The d.b.h. of hemlock tended to increase only slightly with increased spacing, and the variation around the trend was much greater than for Douglas-fir. Spruce and cedar both exhibited an irregular pattern relative to spacing, perhaps because of weevil damage and deer browsing. Growth of both species was apparently depressed by close spacing (arcs 1-6), but it was little affected by spacing beyond arc 6 (1.5-m spacing).

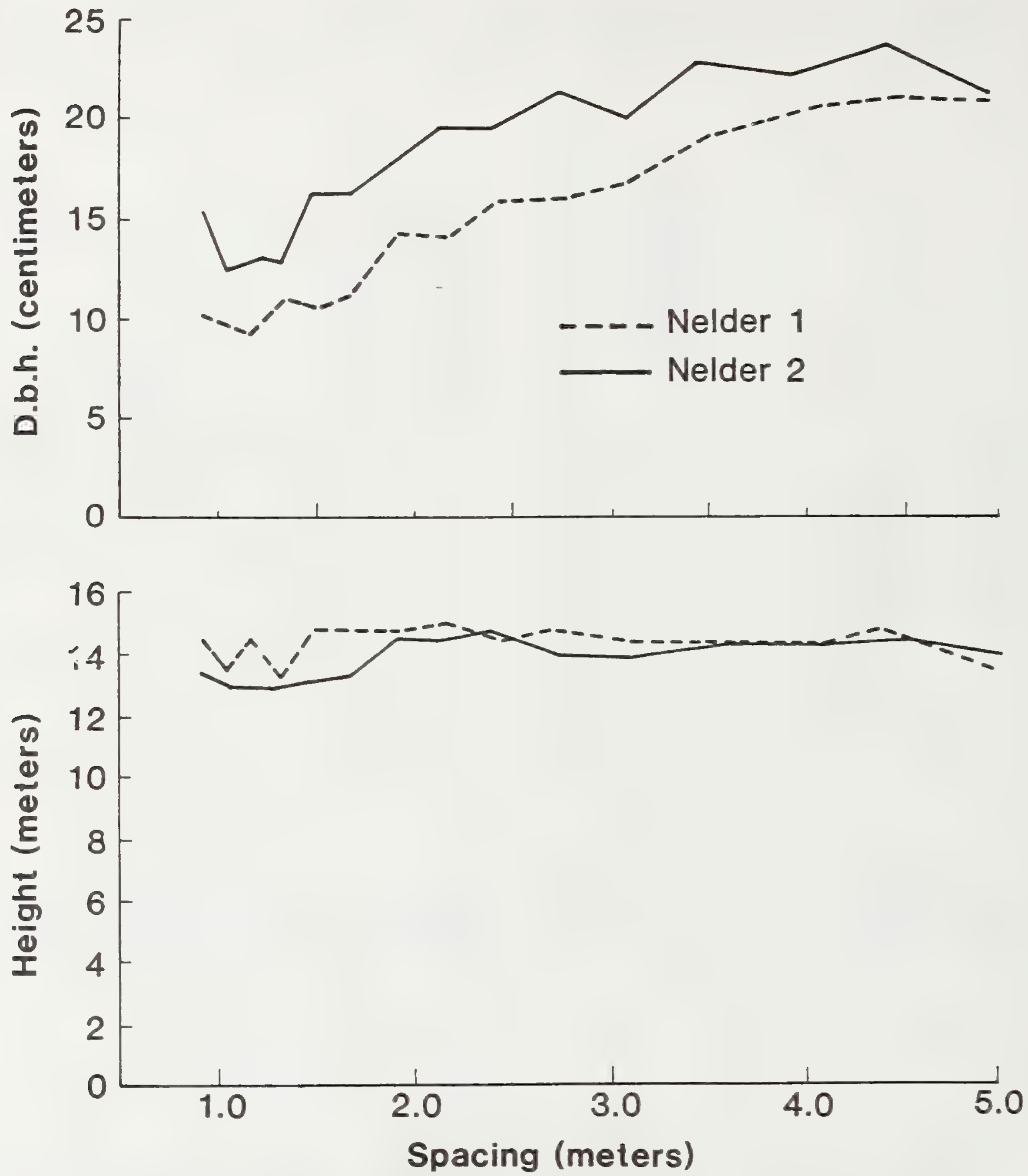

Figure 23—Average d.b.h. and height of Douglas-fir at age 20 by spacing, in Nelder-plots 1 and 2.

As in the other trials, height at age 20 appeared to be little affected by spacing. Average heights of Douglas-fir in Nelder-plot 2 were quite erratic on the inner seven arcs, whereas in Nelder-plot 1, heights were consistently depressed on these arcs (fig. 23). For arcs 8-16 (where spacings were wider than 1.8 m) there was little difference in heights between the two Nelder plots; averages differed by only 0.2 m or 1.4 percent. Height of cedar appeared to be depressed on the inner two or three arcs, but other than that, there was no consistent relation between height and spacing for cedar, hemlock, or spruce. Heights for arcs 8-16 averaged 14.4 m for Douglas-fir, 10.7 m for hemlock, 6.6 m for cedar, and 6.0 m for spruce.

The Variable-Block Trial

The variable-block trial illustrates what might be expected from operational plantings, which include neither replanting to replace dead seedlings nor control of invading vegetation. These stands were so heavily invaded by brush soon after planting that they were abandoned until 1984, when they were remeasured to determine how spacing influenced survival and growth under extreme competition from brush and noncommercial tree species.

Plot boundaries were fitted to areas on which each of the four species—Douglas-fir, western hemlock, western redcedar, and Sitka spruce—were believed to be most appropriate. Assignments of the species and the spacings at which they were planted were based on expected growth, as determined from ecological studies of their behavior in adjacent natural stands.

Despite the heavy, early brush competition, survival and growth were quite good for both Douglas-fir and western hemlock; growth of Douglas-fir was, on the average slightly better than that of hemlock (table 10). Western redcedar and Sitka spruce did much more poorly, primarily because of heavy deer browsing of cedar seedlings and severe weevil damage to spruce. The dense ground vegetation apparently did not have much deleterious effect on stand development.

Table 10—Survival and attained size of trees in the variable-block trial at age 22, by species and by spacing

	Planted		Survivors				Ingrowth
Species 1/	Spacing	Number per hectare	Percent	Number per hectare	Diameter	Height	Number per hectare
	Meters				Centimeters	Meters	
DF	0.91	11,960	25	2,954	8.9	13.0	94
	1.83	2,990	60	1,791	12.1	15.6	382
	4.57	478	67	322	22.0	15.6	53
WH	2.74	1,328	43	575	14.9	13.1	223
	4.57	478	63	301	17.0	13.9	544
WRC	.91	11,960	21	2,512	4.9	--	125
	1.83	2,990	34	1,032	6.9	5.7	186
SS	1.83	2,990	58	1,731	7.3	4.1	70

-- = not applicable.
1/ DF = Douglas-fir, WH = western hemlock, WRC = western redcedar, SS = Sitka spruce.

Mortality of Douglas-fir planted at the 0.9-m spacing was caused by a combination of suppression and snow press. In much of the area planted to Douglas-fir at the 4.6-m spacing, survival was better than the average indicates, and stands fully occupied the sites. Planting more trees to offset expected mortality, as is commonly suggested, would have resulted in overly dense stands and less individual tree growth; in areas where survival was poorer, stocking might have been slightly improved by planting more trees.

Natural regeneration of conifers was highly variable in age, species, and location within the 1.35-ha area. The number of such trees averaged 225 per ha, and plot averages varied irregularly from 53 to 544 per ha. The effects of this natural fill-in were, likewise, quite variable. In some cases, the fill-in provided a desirable supplement to the planted trees. At the other extreme, it sometimes resulted in an extremely high and undesirable level of stand density; this was especially true of a portion of the hemlock plot planted at the 4.6-m spacing, where natural fill-in created a stand density of about 10,000 trees per ha.

The effects of spacing shown in the variable-block trial were comparable to those in the other trials (table 8). Spacing had little effect on height growth but a substantial effect on diameter growth; close spacing may have slightly retarded height growth of Douglas-fir.

Other Factors to Consider

Edge effects may be important. Assessment at age 20 showed no significant differences, however, in rate of growth of edge trees vs. interior trees, probably because all the spacings were associated with other plantations that offered competition at the edges. There was also no distortion of bole shape of edge trees associated with unequal growth of crowns; edge trees did tend to lean slightly away from their more closely spaced neighbors. Elsewhere, in plantations that border on unplanted land (such as Wind River (Reukema 1979)), edge effects can be seen in much better growth of the two outer rows.

The 0.2-ha-plot trial has adequate buffer strips of 1 to 12 rows of trees. The 49-tree-plot trial has no buffers, so this is the trial most likely influenced by edge effects. It would therefore be better for some purposes to analyze only the interior 25 trees, or individual trees. The rectangularity trial has large plots, especially for the five wider spacings; thus, lack of buffers generally had a minimal effect on plot averages. Even though all trees were measured, for some purposes it would be better to analyze only those trees on interior plots. The Nelder plots have "guard arcs" (the innermost and outermost arcs), and Nelder-plot 1 also has "guard spokes" adjacent to the rectangularity quadrant. Effects seldom extended beyond one arc; all spokes were included in the reported averages in this paper. In Nelder-plot 2, only one row in each quadrant is flanked by trees of the same species; thus, a thorough interpretation would require consideration of the position of each tree. In the variable-block trial, most plots are comparable in size to those in the rectangularity trial, so the same comments apply.

Other sources of variation, not related to spacing, included (1) genetic and microsite variation—reflected by early differences in tree size, relation of subsequent growth to early height and diameter, brush development, and effects of site preparation on soil compaction; and (2) damage to seedlings or trees—including root rot pockets, snow press and wind damage, deer browsing of cedar, weevil damage to spruce, and squirrel damage to western hemlock.

Data showed that trees that had superior height or d.b.h. by about 10 years from seed retained that advantage to age 25 regardless of spacing and species. Trees that were initially small generally remained well below the average.

Plantations apparently have some advantages over natural stands. A comparison of height growth in the spacing plantations with heights from stem analyses of naturally established trees on the same area or in nearby stands showed that mean heights and top heights in the plantations started at higher levels and increased their advantage; the planted trees followed superior growth trajectories. Thus, apparent site indices were higher in the plantations.

The UBC spacing trials have provided convincing evidence that advantages of wide spacing increase over time, as has also been seen in the Wind River trial. Trees that showed early superiority at close spacings were not favored by self-thinning among their neighbors to the extent needed to overcome competition; trees released as a result of snow press of their neighbors did not grow fast enough to make up for their early poor crown development compared with trees spaced wide initially.

Relation to Targets

To provide proper perspective, results should be viewed relative to appropriate targets for the first commercial entry. The target is the stand density (level of competition) and average tree size to which one believes a stand should be grown before a thinning is needed to forestall mortality and to maintain tree vigor. Early spacing control determines stand characteristics at this stage of development. This target may be expressed in terms of number of trees per hectare and stand average diameter; the fewer the trees, the larger their size and the older the stand when the target is reached.

Target diameters suggested by Reukema (1975) range from less than 4 cm at the 0.9-m spacing to about 33 cm at the 4.6-m spacing. Corresponding ages at which these targets were reached in the 49-tree-plot and 0.2-ha-plot trials ranged from about age 9 at the 0.9-m spacing to age 22 or 23 at the 3.7-m spacing; it appears that the 4.6-m spacing will reach its target at about age 30. (The Wind River plantations reached target densities from about age 20 with 1.2-m spacing to age 41 with 3.7-m spacing.)

Stands that have only recently reached their target, or have not yet reached it, would be expected to have suffered little spacing-related mortality; the longer the time since the target was reached, the greater the amount of mortality expected. This trend was evident in these trials, but stands reached densities much higher than the suggested target level before substantial mortality occurred. Because trees in the UBC trials were relatively short for their d.b.h., perhaps target diameters should realistically be set somewhat higher (larger). Without thinning, however, all stands will eventually suffer substantial mortality; prior to that, growth rates will probably decline.

Conclusions

Trends over time (in ways other than rates of development) in bole dimensions, crown size and shape, and stand development may have differed among the species. Irregularities from other causes, however, tended to overshadow any such differences. Cedar and hemlock exhibited more variation than Douglas-fir, and the effects of spacing on the time (age or height) when curves began to separate appeared to be different than for Douglas-fir, but data do not permit a positive statement.

Spacing had little effect on average height to age 25. Heights at the close spacings tended to be a little shorter; but for spacings of 1.8 by 1.8 m and wider there were no clear trends. The wider the spacing: the larger the average d.b.h. of both the total stand and fixed numbers or percentages of larger trees; the greater the bole taper; the less the height to live crown; the greater the crown length, crown ratio, and crown width; the less the competition-related mortality; and the less the basal area and volume production per hectare. Differences in average d.b.h. of the total stand and of fixed numbers of largest trees per hectare generally continued to widen over time.

Results suggest that choice of initial spacing is one of the most important decisions made by a stand manager. In economic and biological terms, the 3.7- and 4.6-m spacings appeared to be near optimum for most regimes involving production of lumber. If combined with pruning, those spacings should also be optimum for producing clear lumber and veneer. The 0.9- and 1.8-m spacings should be considered only if the objective is maximum biomass production without regard to tree size. The 2.7-m spacing can produce high yields where thinning is economically feasible, but the additional wood produced would be expensive.

Establishing stands with wide spacings and with rectangularities up to 2:1 resulted in efficient production of large trees of high value and adequate quality. Spacing trees more widely between rows than within rows (rectangular spacing) can (1) reduce planting and tending costs and (2) facilitate extraction and uniform spacing in the first thinning. When funds are scarce and opportunities for thinning are limited, optimum results can be achieved by planting a given number of trees on more land at wider spacing. If demand for clear wood is expected to continue or increase, then planting at spacings such as 6 by 3 m and pruning to a height of 6 m should produce best results; even close spacings cannot control branch size sufficiently to allow trees to grow clear wood on short rotations without pruning.

Acknowledgments

Most of the UBC trials were established by J. Walters, who recently retired as director of the University of British Columbia Research Forest.

Financial support of the Canadian Forestry Service, 1980-83, made possible the collection of data for age 25 and interpretation of results to age 26. Grants from the Natural Sciences and Engineering Research Council of Canada and the British Columbia Ministry of Forests supported some earlier studies.

Dr. Y. El-Kassaby assembled and summarized data for tables and figures, converted pre-1975 data from imperial units to metric units, and did preliminary plotting and interpretation of results.

Data were collected by various research assistants, graduate and senior students, and University Research Forest staff.

English and Metric Equivalents

1 millimeter (mm) = 0.0394 inch
1 centimeter (cm) = 0.3937 inch
1 meter (m) = 3.281 feet
1 hectare (ha) = 2.471 acres
1 tree per hectare (tree/ha) = 0.4047 tree per acre
1 square meter per hectare (m^2/ha) = 4.356 square feet per acre
1 cubic meter hectare (m^3/ha) = 14.29 cubic feet per acre
1 kilometer (km) = 0.6214 mile
1 °C = (°F-32)/1.8

1 inch (in) = 2.54 centimeters
1 foot (ft) = 0.3048 meter
1 acre (ac) = 0.4047 hectare
1 tree per acre (tree/ac) = 2.471 trees per hectare
1 square foot per acre (ft^2/ac) = 0.2296 square meter per hectare
1 cubic foot per acre (ft^3/ac) = 0.06997 cubic meter per hectare
1 mile (mi) = 1.609 kilometers
1 °F = (9/5 °C) + 32

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Appendix

Table 11—Number of trees per hectare, plot size, and number of trees per plot, by trial, plot number, species, and spacing

Trial	Plot number	Species 1/	Spacing	Nominal number of trees per hectare	Plot size	Nominal number of trees per plot
			Meters		Hectare	
49-tree-plot 2/	19	DF	0.9 by 0.9	11,961	0.0082	98
			1.8 by 1.8	2,990	.0164	49
			2.7 by 2.7	1,329	.0369	49
			3.7 by 3.7	748	.0655	49
			4.6 by 4.6	478	.1025	49
	20	WRC	0.9 by 0.9	11,961	.0082	98
			1.8 by 1.8	2,990	.0164	49
			2.7 by 2.7	1,329	.0369	49
			3.7 by 3.7	748	.0655	49
			4.6 by 4.6	478	.1025	49
	21	WH	0.9 by 0.9	11,961	.0082	98
			1.8 by 1.8	2,990	.0164	49
			2.7 by 2.7	1,329	.0369	49
			3.7 by 3.7	748	.0655	49
			4.6 by 4.6	478	.1025	49
0.2-ha plots	15	DF	0.9 by 0.9	11,961	.1977	2,365
	17		1.8 by 1.8	2,990	.2154	644
	14		2.7 by 2.7	1,329	.2144	285
	16		3.7 by 3.7	748	.2406	180
	18		4.6 by 4.6	478	.2510	120
	34	WH	0.9 by 0.9	11,961	.1913	2,288
Rectangularity	46	DF	0.9 by 0.9	11,961	.0326	390
	51		1.4 by 1.4	5,316	.0705	375
	54		1.8 by 1.8	2,990	.1207	361
	47		1.8 by 2.7	1,994	.1906	380
	50		1.8 by 3.7	1,495	.2669	399
	53		2.7 by 2.7	1,329	.2739	364
	52		2.7 by 3.7	997	.2889	288
	49		2.7 by 4.6	797	.4743	378
	48		2.7 by 5.5	665	.5895	392
	62	DF/WH	0.9 by 0.9	11,961	.0522	624
	59		1.4 by 1.4	5,316	.0752	400
	58		1.8 by 1.8	2,990	.1271	380
	60		1.8 by 2.7	1,994	.2287	456
	56		1.8 by 3.7	1,495	.2528	378
	63		2.7 by 2.7	1,329	.3792	504
	57		2.7 by 3.7	997	.3932	392
	61		2.7 by 4.6	797	.3513	280
	55		2.7 by 5.5	665	.5895	392
Nelder	1	DF	Variable	--	.6187	3/ 780
	2	mixed 4/	Variable	--	.6187	816
Variable-block	70	DF	0.9 by 0.9	11,961	.0319	381
	69		1.8 by 1.8	2,990	.1017	304
	65		4.6 by 4.6	478	.3013	144
	68	WH	2.7 by 2.7	1,329	.2814	374
	66		4.6 by 4.6	478	.2259	108
	71	WRC	0.9 by 0.9	11,961	.0402	481
	64		1.8 by 1.8	2,990	.2532	757
	67	SS	1.8 by 1.8	2,990	.1144	342

-- = not applicable.
1/ DF = Douglas-fir, WH = western hemlock, WRC = western redcedar, SS = Sitka spruce.
2/ 2 plots for each spacing. Plots at 0.9-m spacing have 98 trees each.
3/ In Nelder-plot 1, 36 contiguous spokes with 612 trees are used to test variable square spacings, and 12 spokes with 168 trees are used to test rectangular spacings.
4/ In Nelder-plot 2, 4 species (DF, WRC, WH, and SS) are each included successively in groups of 3 spokes. The sequence is repeated 4 times.

Reukema, Donald L.; Smith, J. Harry G. Development over 25 years of Douglas-fir, western hemlock, and western redcedar planted at various spacings on a very good site in British Columbia. Res. Pap. PNW-RP-381. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; **1987.** 46 p.

Results of five spacing trials on the University of British Columbia Research Forest, covering a range of plantation spacings from 1 to 5 meters, showed that choice of initial spacing is among the most important factors influencing bole and crown development and stand growth and yield. The trials include Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*). The results to date should help managers to choose optimum spacings for their purposes. Initial wide spacings with rectangularities up to 2:1, such as 6 by 3 meters, resulted in efficient production of large trees of high value and satisfactory quality. Pruning of widely spaced trees to enhance quality of the lower bole is strongly recommended.

Keywords: Plantation spacing, (-growth, stand development, density, height increment, diameter increment, crown development.

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